THE MAKING, SHAPING AND TREATING OF STEEL

CARNEGIE STEEL COMPANY
BUREAU OF INSTRUCTION

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THE MAKING, SHAPING AND TREATING OF STEEL

BY
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AND
C. B. FRANCIS

FOURTH EDITION

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PREFACE TO FOURTH EDITION

The rapid march of progress in the iron and steel industry and the unexpectedly large demand for this book have made it necessary to issue four editions all within the comparatively brief period of six years. In preparing this edition we have not permitted ourselves to lose sight of either of these factors. To keep the book abreast of the times, we have carefully revised, changed or corrected, all the material of the previous editions, rewriting many of the sections and changing the wording or the data of others wherever necessary to bring them up to date. To make the book more valuable to the many different classes of readers among whom it is now in demand, its scope has been considerably enlarged, making the present volume about twice the size of the second and third editions.

In selecting this new material we have aimed to supply the knowledge most useful to five different classes of readers; namely, employees of Carnegie Steel Company, employees of the other subsidiary companies of the United States Steel Corporation, customers of these companies, students of Ferrous Metallurgy in colleges and universities, and the general reader who desires a work for reference. Consequently, we have added a chapter on wrought iron; another on early methods of making steel; three sections on the acid open hearth process; four sections on molybdenum, manganese, and silicon steels, thus completing the chapter on Structural Alloy Steels; a chapter on fine steels, including high speed and other tool steels; and one chapter each on steel wire, sheets, tin plate and tubular products. In dealing with these new subjects, we have held to our original determination, namely, to play the parts of neither historians nor prophets, but simply to tell the truth about things as we find them today. Realizing, however, the value of history to the student as a guide to avoid repeating the mistakes of others, we have introduced such historical facts as we thought would prove to be most useful to our readers.

In conclusion, we wish to thank the officials, and many of the superintendents and foremen, of the various subsidiary companies of the United

States Steel Corporation for their cöoperation during the preparation of the chapters or sections on their respective products. We also appreciate the suggestions received from many of our readers and critics. Their frank expressions have been a great aid in overcoming some of the shortcomings of the previous editions. For example, the two chief faults found with the former editions were that some parts of the book were not adequately illustrated for readers who do not have the advantage of access to the mills, and that the scope of the work did not justify the title. In this edition an earnest endeavor has been made to remove both of these objections. Finally, we wish to acknowledge the kindly assistance of many individuals and firms, the names of most of whom will be found scattered throughout the text.

J. M. C.

C. B. F.

Pittsburgh, Pa.

June 1, 1925.

PREFACE TO SECOND AND THIRD EDITIONS

This book has been written especially for the non-technical employees of the Carnegie Steel Company, and others, who, seeking self instruction, may desire to secure in the shortest time possible a general knowledge of the metallurgy of iron and steel.

The book is the outcome of several years experience in attempting to teach the metallurgy of steel to our salesmen and other non-technical employees. From the first, the method pursued in this work has been that of taking the students, under proper guidance, into the mills, where they obtain, first hand and individually, such information as they desire and are able to collect, and of supplementing the knowledge gained from these visits with talks and explanations delivered in a classroom where conditions are more favorable for this kind of instruction than they are in the mills. These talks, in a condensed form, were put in writing, and a copy given to each of the students. As the demand for these lectures increased, it was decided that, for the sake of convenience, they should be printed; and accordingly they were revised and are here assembled in the present volume.

In order to increase the value of the book as a reference book, we have aimed to condense the information and to avoid every unnecessary word, both by omitting all matter from the text not absolutely essential and by the free use of tables, drawings and diagrams, which we permit to tell their own story. However, knowing our readers will be men imbued with a desire to learn, we have not avoided discussing many scientific aspects of our subjects. But here we have tried to make it easy even for the general reader. We have aimed to use language as simple as possible, consistent with clearness, and to treat our subjects in such a way that, aside from what a limited education supplies, no prerequisites will be required. We start with the elementary subjects of Physics and Chemistry, the logical prerequisites, and build our metallurgy upon that foundation. The book will, therefore, prove of most value to those

connected with the steel business, and not technically educated, who are really anxious to learn more about the wonderful industry in which they are engaged. For such as these, we have aimed to make this book at least a stepping stone to higher and better things.

With regard to the subject matter of the book, we claim but little in the way of originality. We have no new theories to advance and no new discoveries to reveal. Our aim throughout has been to describe conditions and things as they are and to explain the causes for their being as they are, rather than to tell how they might be or how they ought to be. To accomplish our first purpose, we have been compelled to rely mainly upon our personal observation and experiences, but in explaining the causes of things we have freely consulted all those whose published opinions relating to each particular subject have been available and of value. We are, therefore, indebted to many for aid, and to all these we wish to express our thanks. Wherever we have drawn upon these sources of information we have aimed to give the credit to the authors by mention in the text or by foot note references. As guides to collateral reading these references will have an additional value to our readers. We also desire to thank the superintendents and the many heads of departments of our various plants for the courtesies they have shown us and for the many bits of valuable information which they were ever ready to give.

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PART 1.

THE MAKING OF STEEL.

CHAPTER 1.

SOME FUNDAMENTAL PRINCIPLES OF PHYSICS AND CHEMISTRY.

SECTION 1.

INTRODUCTION.

1. Iron, the Master Metal: In beginning this rather brief study of the metallurgy of the most important metal of a metallic age, it is difficult to refrain from pointing out a few of the qualities that have made iron the master metal, although its importance really needs no comment here. A little reflection shows it to be as vital to modern civilization as air and water are to life; and it has become so common that, like air and water, its true importance is lost sight of by most people, who look upon its abundance as a matter of course and value it accordingly. No other one metal has contributed so much to the welfare and comfort of man. There is scarcely an article used in our daily lives that has not been produced from iron or by means of it. Consider bread as an example. Plows made of iron turn the soil, harrows of iron level it, and drills of iron sow the seed; machines of iron harvest the wheat and thrash it; rolls of iron crush the grain to separate the flour; engines of iron bring the flour to our homes, where it is made into dough in iron pans and baked in an iron stove; finally the bread is sliced from the loaf with an iron knife, and served to us at a table made with iron tools. It has no exact substitute in nature, and without it most of our modern conveniences would have been impossible of development. The railroads, the automobile, and the watch are three of the many notable examples of such conveniences. No other metal is capable of giving the great range in physical properties that makes iron available for an almost unlimited number of purposes. Thus, from our towering skyscrapers, our massive bridges and our immense ships, where, as great beams, cables and plates, it supports loads almost greater than the mind can conceive, we can trace it even to our parlors, where, as invisible hairpins, it may support milady's tresses and, as the strings of her piano, it sends forth at her magic touch sweet sounds of melody. One property which it possesses in a far greater degree than any of the other metals is that of magnetism. This property is so pronounced in iron and so slight in other metals that, from a practical viewpoint, iron and one of its compounds may be considered as the only magnetic substances. Hence, our modern magnetic

and electrical appliances are dependent upon this one metal; and we find it forming the essential parts of the dynamo, the electric motor, the telegraph, the telephone, the wireless telegraph, the compass, and a large number of other instruments of less importance. And so we might continue at great length upon this one topic of the importance of iron, but our time is too short to permit our giving much of it to a theme which the reader may develop for himself. Hastening on, then, to more important matters, we find the first question that confronts us is, What is Metallurgy?

Metallurgy: In general, Metallurgy is defined as the science which deals with the preparation of the metals and their adaptation to the uses for which they are intended. It is an advanced and specialized science, hence a difficult one. Even a slight understanding of the subject requires a previous knowledge of the fundamental sciences of Physics and Chemistry. For those who may not have had the necessary preparation in these prerequisites, this study is becomingly introduced by a brief consideration of some of the more important principles of these two sciences. To present these principles in as concise and simple a manner as possible is the object of this chapter.

Matter: Through the various senses of sight, touch and hearing, the human intellect becomes aware of the existence of things which, collectively, are called matter. Matter contained in a limited portion of space is termed a body, and the different kinds of matter are, in general, spoken of as substances. Matter is a fundamental thing and cannot be accurately defined. It is described by its properties, which will be discussed later.

The Fundamental Law and the States of Matter: Certain facts about matter, however, are plainly evident. It occupies space, and can be neither increased nor decreased in amount. These last two facts are commonly known as the Law of the Conservation of Matter. It exists in any one of three states; solids, which have definite masses, sizes and shapes; liquids, which have definite masses and sizes but not form; and gases, which possess definite masses only. A common example is water, which at ordinary temperatures exists in all three states; namely, ice, water and vapor. Liquids and gases together are called fluids on account of their flowing properties, and in many instances they are subject to the same laws. They are distinguished from each other by their relative compressibility. Liquids are but slightly compressible, while gases are highly compressible. **The volume of a gas varies inversely as the pressure applied to it.** For example, if a certain mass of gas has a volume of 10 cu. ft. under a pressure of 100 lbs., the same mass of gas will occupy but 5 cu. ft. at 200 lbs. pressure.

Molecules: Furthermore, while the conception may seem difficult to establish as a fact, there are strong reasons for believing that the relatively large bodies, in which form matter makes itself evident to the human senses, are composed of minute particles, called molecules. This belief is

founded upon many facts, and can be arrived at by some such process of reasoning as follows: Mental conception concerning the constitution of matter may be based on either one of two hypotheses; namely, that matter is infinitely divisible or that it is made up of small particles. According to the first hypothesis, a body of matter could be divided indefinitely, if means were available to make such a process possible, without changing any of its characteristics, except its size; that is, a piece of chalk, for example, would remain chalk even as the particles resulting from the infinite division approached zero in size and weight. This retention of original characteristics would imply that each individual kind of matter, the chalk in the present instance, is an elementary substance. But this conclusion is contrary to the facts, for it is a matter of common knowledge that many substances like iron ore, limestone, sugar, etc., are composed of substances quite different from the original. Thus, through the application of heat alone, limestone and sugar are decomposed, the former into quick lime and carbonic acid gas, and the latter into carbon, or charcoal, and water. Only the second hypothesis remains, and it agrees with these facts, for it assumes that the larger masses of limestone and sugar, so evident to our senses, are made up of small particles, each of which is composed of portions of these simpler things into which the limestone and sugar are decomposed by the heat. These ultimate particles of the different substances are called molecules, which are, therefore, defined as the smallest particles of a substance that retain the characteristics of that substance.

Sciences of Matter: Two great classes of matter are evident; animate or living matter, such as the living bodies of plants and animals, and inanimate matter, such as glass, water, air, etc. Animate matter is treated of by the sciences of Biology, Zoology and Botany; inanimate, by Physics and Chemistry, formerly included under the one head of Natural Philosophy. Thus, Metallurgy may be looked upon as a highly specialized branch of Natural Philosophy. All these sciences are so closely related that a knowledge of all is essential to a complete understanding of any one.

SECTION II.

SOME PHYSICAL PROPERTIES OF MATTER.

Properties: That a better understanding of matter may be obtained from a study of its properties has already been indicated. By properties is meant those characteristics by which the different kinds of matter are distinguished and by which it may be described and defined. They are of two classes,—namely, general and special. General properties are common to all matter, while special properties are peculiar to certain kinds of matter only. The general properties are as follows:

Inertia: This property causes matter to resist any attempt to change its state of rest or motion.

Extension is that property by virtue of which matter occupies space. There are two systems of measuring extension, the English and the metric. In the English system, the linear unit is the yard, while the volumetric units, as established by custom, are the gallon, the bushel, and the cubic yard. Corresponding units in the metric system are the meter=1.09361 yards=39.37 inches; the kilometer=.62137 mile; the liter=.26417 gallon=1.0567 quarts, liquid, or .908 quart, dry; and the cubic meter=1.308 cubic yards.

Mass, commonly taken as the amount of matter in a body or as the measure of its inertia, is an inherent property of any body, independent of the kind of matter of which the body is composed and of its position with reference to other bodies. These facts distinguish it from weight, which is defined as the force with which a body is attracted to the earth. The metric unit is the gram, practically equivalent to a cubic centimeter of water at 4°C. For commercial purposes the kilogram=1000 grams=2.20462 pounds avoirdupois is the unit used.

Density is the weight or mass of a unit volume of matter. It is usually expressed in grams per cubic centimeter.

Specific Gravity is the number of times a body is heavier than an equal volume of some substance used as a standard. For liquids and solids this standard is water; for gases it is air or hydrogen. In the metric system density and specific gravity are numerically the same, since the weight of one cubic centimeter of water is one gram.

Porosity: All matter is porous. The molecules, it is thought, are separated, even in the densest materials, by spaces larger than the molecules themselves.

Impenetrability: Two bodies of matter cannot occupy the same space at the same time, and to this property of matter the term impenetrability is applied.

Special Properties: The chief special properties of matter, some of which are of supreme importance in the manufacture of steel, are as follows:

Cohesion and Adhesion: According to the law of gravitation, every particle of matter in the physical universe attracts every other particle with a force whose direction is that of a line joining the two particles and whose magnitude varies directly as the product of the two masses, and inversely as the square of the distance between them. Applied to molecules, this attraction is known as cohesion and adhesion; the former is the attraction of molecules of the same kind for each other, the latter, the attraction of unlike molecules. The clinging of a drop of water to the end of a glass rod exemplifies both of these forces.

Elasticity is the power of matter to assume its original shape after having been distorted. The property of cohesion causes all bodies to resist change in form, but only solids have elasticity of form. When a solid body

is deformed, the resistance it offers is called the **stress;** the deformation which produces this stress is called the **strain.** Hooke's law states that, up to the elastic limit, the strain is proportional to the stress. In practice, the stress is measured in terms of a force or forces applied externally to the body being tested. There are four methods of calling forth the elasticity of bodies:—namely, by pressure, by stretching, by bending and by twisting. Stretching and bending are the methods most commonly employed in testing the elasticity of steel.

Plasticity is the opposite of elasticity. A plastic body once distorted will not regain its original shape.

Ductility is sometimes defined as the property by virtue of which matter may be drawn into fine wires. As the term is employed in the testing of steel, ductility is the distortion or strain a body undergoes in being ruptured.

Malleability: Some kinds of matter, metals in particular, can be hammered or rolled into thin sheets. This property is called malleability.

Hardness is the ability to withstand abrasion, or resist penetration.

Crystallization: Some substances, in changing from a liquid to a solid form, separate not as a continuous compact mass but as bodies having a definite shape and color, called crystals. That crystals may form, it is necessary that the molecules be free to arrange themselves in a definite order. This condition is secured when a substance is in solution or in a molten state. In steel manufacture this property is of great importance.

Diffusion is most characteristic of liquids and gases. It is the property that causes two fluids in contact to intermingle. Liquids diffuse slowly, but gases much more rapidly.

Effusion is the term applied to that property of gases which causes them to pass through porous solids. The rates of effusion of different gases is inversely proportioned to the square roots of their relative weights.

Absorption: Many porous bodies, like coke, charcoal, platinum sponge, etc., are capable of absorbing large quantities of gases. Thus, one cubic centimeter of charcoal is capable of absorbing from thirty to thirty-five times its own volume of carbon dioxide. Gases are condensed on the surface of all solids, and porous bodies offer a large surface for condensation.

SECTION III.

ENERGY, HEAT AND TEMPERATURE, AND THE ETHER.

Energy: Physics and Chemistry, however, have to do with more than matter. The senses also reveal the presence of a second factor in nature, called energy. Like matter, energy is a fundamental that cannot be satisfactorily defined. It is not a thing. It is that which gives a body the ability to move against a resistance; that is, the ability to do work.

Thus, a body may possess energy and still neither move nor do any work. Like matter, energy is conserved. It may be changed from one form to another or be transferred from one point to another, but the total energy of the Universe remains constant. This fact is known as the Law of Conservation of Energy.

Kinds of Energy: There are two kinds of energy; namely, potential or stored up energy, sometimes called energy of position, and kinetic energy, or the energy possessed by a body by virtue of its motion. Thus, a weight on the top of a building possesses potential energy with respect to the ground by virtue of its position; if it is permitted to fall, its energy then becomes kinetic. Energy is measured in terms of the work which it is capable of doing.

Heat and Temperature: One form of energy is heat. Heat must not be confused with temperature. The latter measures one of the effects of the former. The difference may be illustrated thus:—Let it be supposed that two portions of natural gas, each of a cubic foot, are burned completely, so that the heat liberated is entirely absorbed by two bodies of water initially at the same temperature, the volumes of which are a quart and a gallon, respectively. It is evident from common experience that the temperature of the smaller portion of water will be raised the higher, though the quantity of heat imparted to each is precisely the same.

Effects of Heat: Heat produces marked effects on matter. All matter expands by the application of heat alone, though there are many apparent exceptions. The **volume of a gas varies directly as the absolute temperature,** other conditions remaining constant. Change of state may be caused by heat. Thus, glass or iron, dense solids at ordinary temperatures, readily assume the fluid state on being heated above their fusion point. According to the kinetic theory of heat, the molecules of matter always have a certain amount of independent motion, and the effect of adding heat is to increase the energy of this motion, the molecules being thereby forced farther and farther apart. This forcing apart of the molecules accounts for the change of state as well as the expansion of bodies on being heated.

Temperature is determined by measuring the expansion it produces in a volume of mercury enclosed in a small glass tube, called a thermometer. The length of the tube is marked off into small divisions, which constitutes the scale of the thermometer. There are four thermometer scales in common use; the Centigrade, Fahrenheit, Reaumur and Absolute. The difference among them consists of the number of divisions between the freezing point and the boiling point of water, and the numbers applied to these divisions.

The Centigrade is the thermometer employed in all scientific work. In it the freezing point is marked zero and the boiling point 100°. The only

difference between this scale and the Absolute is that, in the latter, the zero point is 273° below the Centigrade zero.

In the Fahrenheit thermometer, the space between the freezing and the boiling points is divided into 180 equal parts, and zero is 32 of these parts below the freezing point of water. The boiling point, therefore, is 212°.

In the Reaumur scale, the freezing point is marked zero and the boiling point 80°.

These relations of the various scales are shown in the accompanying diagram: From this diagram the following formulas are readily developed:

Temp. A=Temp. C+273.

Temp. C=Temp. A—273.

Temp. F=Temp. 9/5C+32.

Temp. C=Temp. (F—32°)5/9

For high temperatures, instruments called pyrometers are used.

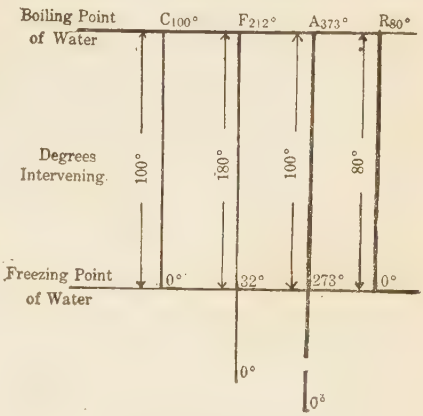


Fig. 1. Diagram showing relations of the various thermometer scales.

Measurement of Heat: Heat is measured in calories. A calorie (cal.) is the heat required to raise the temperature of one gram of water one degree centigrade. In practice the large calorie (Cal.) is employed. It is the amount of heat required to raise one kilogram of water through one degree centigrade. The corresponding unit in the English system is the B. t. u. (British thermal unit), which is the heat required to raise the temperature of one pound of water one degree Fahrenheit. These units may be converted from one to the other by use of the following factors:

1 Calorie=3.968 B. t. u. or
1 B. t. u.= .252 Cal.

The Ether: A third factor composing the Universe is the Ether. Little is known about it except that it fills all space, permeates all matter and transmits light, heat, and electric waves. Its properties are very difficult to analyze, because the senses are not directly affected by it. Its presence was first suspected through the study of the transmission of light. By comparatively simple experiments, it was shown as early as 1802 that light is transmitted by a wave motion, and since light is transmitted through a vacuum, something other than matter must act as the medium. The same conclusion is arrived at by a study of heat radiation. The development of wireless telegraphy and the radio was based on this supposition, and their success is further evidence of the existence of the Ether.

SECTION IV.

CHANGES IN MATTER.

Physical and Chemical Changes: Matter is constantly undergoing changes. A close observer soon discerns that these changes are of two kinds,—namely, one in which the nature and composition of the matter undergoing the change remains the same, called a **physical change,** and another in which the nature and composition are affected, called a **chemical change.** The bending of a stick, the freezing of water, the fusion of steel are examples of the former, while the burning of coal is a common example of the second. In many physical changes and in all chemical changes heat is involved,—being either absorbed or liberated. Chemical changes that liberate heat furnish a source of energy— **chemical energy.**

The Make-up of Material Bodies: In considering the make-up of the various bodies of matter, it is necessary to distinguish between mere mixtures and more closely combined substances. **A mechanical mixture** is a mixture of two or more substances, which is not homogeneous, that is, its constituents can be separated by mechanical means. Such mixtures are made up of molecules of different kinds. **A chemical compound** is homogeneous throughout its mass, and its constituents cannot be separated by mechanical means, that is, its molecules are all of the same kind. The components of any given chemical compound are always in the same proportions for that compound. This fact distinguishes compounds from **alloys** and **solutions** which, though they are practically homogeneous and sometimes are practically impossible of separation by mechanical means, are never constant in composition. An alloy is a metallic substance, the components of which are wholly or partly soluble in each other in the liquid state, that is to say, any metallic substance not a chemical element.

Kinds of Chemical Compounds: A close study of a great number of chemical compounds will show that these substances fall into four classes; namely, acids, bases, salts and non-electrolytes.

Acids are characterized by the fact that they all have a sour taste when in water solution and change the color of certain chemicals, called indicators. One of the most common of these indicators is litmus, of which there are two colors, a blue and a red. Acids change the color of blue litmus to red. Vinegar is chiefly a dilute solution of acetic acid.

Bases have the power of neutralizing acids, and may be looked upon as their opposites. Examples are quick lime, lye, etc. Bases change the color of red or neutral litmus to blue.

A Salt is the product formed when an acid is neutralized by a base. Common table salt, made by neutralizing hydrochloric acid with sodium carbonate, is an example. As a rule acids, bases, and salts are electrolytes, that is, their water solutions will conduct the electric current.

Non Electrolytes: There are some compounds that do not resemble either acids or bases, nor can they be classed as salts. They are characterized by the fact that their water solutions will not conduct the electric current, so are termed non-electrolytes. Benzene, methane and distilled water are examples.

Chemical Elements: Notwithstanding the fact that chemical compounds are homogeneous and cannot be separated by mechanical means, they are readily divided into simpler substances by chemical processes. These simpler substances are called elements, and each and every chemical compound is composed of two or more chemical elements. While the number of chemical compounds is almost unlimited, there are comparatively few elements. In 1925, the discovery of 86 elements had been reported. The total number is probably not over 92. Of these, twelve compose about 99 per cent. of the earth's crust. It has been estimated that the solid crust of the earth is made up approximately as follows:

Oxygen	49.85%	Calcium	3.18%	Hydrogen	.97%
Silicon	26.03%	Sodium	2.33%	Titanium	.41%
Aluminum	7.28%	Potassium	2.33%	Chlorine	.20%
Iron	4.12%	Magnesium	2.11%	Carbon	.19%

TOTAL 99.00%

Classification of Chemical Elements: A study of the elements reveals the fact that there are two great classes; namely, those that combine with oxygen and hydrogen to form bases, and those that combine with oxygen and hydrogen, or hydrogen alone, to form acids. The former are sometimes called **metals** and the latter **non-metals,** or **metalloids.** The line of division is not a sharp one. Some elements form both acids and bases, but the tendency is more pronounced in the one direction than in the other. Furthermore, like plants or animals, these two divisions may be sub-divided into families or groups, the members of which possess similar properties. These divisions and groups are shown in a subjoined table.

Symbols: For convenience and brevity, each element is represented by a symbol. These symbols are composed of the first letter, capitalized, of the English or Latin names of the elements, combined, where necessary as a distinguishing mark, with some succeeding letter. Thus, C=carbon, Ca=calcium, Cd=cadmium, F=fluorine, Fe=ferrum (iron), etc.

Fundamental Laws of Chemical Changes: Now, **where the elements combine to form a compound they always do so in definite proportions by weight.** Thus, fifty-six parts by weight of iron will combine with sixteen parts by weight of oxygen, or fourteen parts by weight of nitrogen with sixteen parts by weight of oxygen. This fact is known as the **Law of Definite Proportions,** and the definite weights are called combining weights. Further investigation along this line shows that some pairs of elements form more than one compound and that the combining weights of the elements in these different compounds are simple multiples of each other. Concisely stated, the law is this: **Whenever two elements unite to form more than one compound, if we consider a fixed weight of the one, the weights of the other which combine with it are integral multiples of one another.** This fact is known as the **Law of Multiple Proportions,** or Dalton's second law. The following compounds formed by the two

elements nitrogen and oxygen are well known examples:

Compound	Parts by Weight of Nitrogen	Parts by Weight of Oxygen
Nitrous Oxide	28	16
Nitric Oxide	28	32
Nitrogen Trioxide	28	48
Nitrogen Peroxide	28	64
Nitrogen Pentoxide	28	80

SECTION V.

THE ATOMIC AND ELECTRON THEORIES.

Atoms: Upon the facts just stated in the preceding section, the English chemist Dalton founded a very important hypothesis, now known as the atomic theory. In order to explain the laws stated above, reasoning led to the following assumptions:

1st: The molecules of matter are themselves made up of small particles.

2d: These particles possess the power of attracting other particles or otherwise attaching themselves to them.

3d: These particles do not subdivide in taking part in chemical changes.

These particles are called atoms. All the atoms of the same element have the same mass or weight, the same form, and the same combining power, while atoms of different elements differ in one or more of these respects.

Atomic Weights: The atom is so small that it is useless to hope that its mass or weight will ever be determined absolutely. However, the weight of one atom of an element must be proportional to the combining weight of that element. Since the combining mass or weight of hydrogen is the least of all the other elements, it is assumed that its atom is the lightest. Therefore, the atomic weight of hydrogen was made one by Dalton and the atomic weight of the other elements multiples of it. However, since hydrogen forms with other elements comparatively few compounds that can be used for atomic weight determinations and oxygen more than any other element, it was decided later to make the latter element the standard. Accordingly, the atomic weight of oxygen is made 16, and the atomic weights of other elements are compared with it as a standard, thus making hydrogen 1.008. This system of comparative weights is known as the international table of atomic weights.

Valence: Concerning the attractive power of the atoms of the various elements, it may be pointed out that the law of multiple proportions indicates that the atom of an element may combine with one or more atoms of another element in forming compounds with it. Here, again, hydrogen is used as a standard, for since its combining weight is the least of all the other elements, it is assumed that the holding power of its atoms must also be the least. Therefore, **the valency of an atom is properly defined as the number of hydrogen atoms it is capable of combining with or replacing.** The valencies of the atoms of the elements are by no means fixed quantities, but vary—in some cases from one to seven.

The following table is intended to furnish a complete list of the elements, with their symbols and atomic weights, and to show, also, the classification and valencies of the more common ones. Very rare elements are placed in a separate list. Elements that ordinarily are both acid and basic are marked with an *, and those important in the manufacture of steel are printed in Italics.

Table I—The Chemical Elements.

Showing Physical Constants of the More Common Ones.

Class	Group	Name	Symbol	1925 Atomic Weights O=16	Valence	Specific Gravity Water	Specific Gravity Air	Melting Point °C	Boiling Point °C
BASE FORMING	Potassium	Lithium	Li	6.94	I	.534	....	186	1400
		Potassium	*K*	*39.096*	*I*	*.851*	....	*62.3*	*710*
		Sodium	*Na*	*22.997*	*I*	*.952*	....	*97.5*	*750*
	Calcium	*Calcium*	*Ca*	*40.07*	*II*	*1.54*	....	*810*	.....
		Barium	Ba	137.37	II	3.8	....	850	950
		Glucinum	Gl	9.02	II	1.85	....	1280	.....
		Strontium	Sr	87.63	II	2.5	....	830?	.....
	Magnesium	*Magnesium*	*Mg*	*24.32*	*II*	*1.7*	....	*651*	*1120*
		Zinc	Zn	65.38	II	7.1	....	419.4	930
		Cadmium	Cd	112.41	II	8.6	....	320.9	778
	Silver	Silver	Ag	107.880	I	10.5	....	960.5	*1955*
		Copper	*Cu*	*63.57*	*I-II*	*8.9*	....	*1083*	*2300*
		Mercury	Hg	200.61	I-II	13.60	....	−38.87	357
	Aluminum	**Aluminum*	*Al*	*26.97*	*III*	*2.7*	....	658.7	1800
		Gallium (rare)	Ga	69.72	.....	5.95	....	30	2000
		Thallium "	Tl	204.39	.....	11.85	....	302	1280
		Scandium "	Sc	45.10	.....	.....	....	*1400?*	.....
	Lead	*Lead	Pb	207.20	II-IV	11.3	....	327.4	1525
		*Tin	Sn	118.70	II-IV	7—7.3	....	231.9	2270
	Chromium	*Chromium	*Cr*	*52.01*	*II-III-VI*	*6.9*	....	*1615*	*2200*
		*Molybdenum	*Mo*	*96.0*	*III-IV-VI*	*8.8*	....	*2550*	*3600*
		*Tungsten	*W*	*184.0*	*IV-V-VI*	*18.8*	....	*3400*	*5800*
	Manganese	*Manganese	*Mn*	*54.93*	*II-IV*	*7.4*	....	*1230*	*1900*
	Iron	*Iron*	*Fe*	*55.84*	*II-III*	*7.86*	....	*1530*	*2450*
		Cobalt	*Co*	*58.94*	*II-III*	*8.7*	....	*1480*	.....
		Nickel	*Ni*	*58.69*	*II-III*	*8.7*	....	*1452*	.....
	Palladium	*Palladium	Pd	106.7	*I-II-IV*	12.2	....	*1550*	.....
		Ruthenium (rare)	Ru	101.7	.....	12.1	....	*2450?*	.....
		Rhodium (rare)	Rh	102.91	.....	12.4	....	*1950*	.....
	Gold	*Platinum	Pt	195.23	IV	21.37	....	1755	3900
		*Gold	Au	197.2	I-III	19.3	....	1063	2530

Table I—The Chemical Elements—Continued.

Class	Group	Name	Symbol	1925 Atomic Weights 0=16	Valence	Specific Gravity Water	Specific Gravity Air	Melting Point °C	Boiling Point °C
ACID FORMING	Chlorine..	*Fluorine*.....	*F*	*19.00*	*I*	*1.14*	*1.31*	*—223*	*—187*
		Chlorine.....	*Cl*	*35.457*	*I*	*1.51*	*2.49*	*—101.5*	*—37.6*
		Bromine.....	Br	79.916	I	3.1	5.52	—7.3	59
		Iodine.....	I	126.932	I	4.9	....	113.5	184
	Sulphur...	*Sulphur*.....	*S*	*32.064*	*II-IV-VI*	*2.0*	....	*112.8 / 119.2 / 106.8*	*444.6*
		Selenium (rare)..	Se	79.2	.....	4.3	....	218.5	690
		Tellurium " ..	Te	127.5	.....	6.2	....	452	1390
	Carbon...	*Carbon*.....	*C*	*12.000*	*IV*	*1.7-3.5*	....	Infusible	*3500*
		Silicon.....	*Si*	*28.06*	*IV*	*2.42*	....	*1420*	3500
		Boron.....	B	10.82	III	2.54	....	*2250?*	3500
		Titanium.....	*Ti*	*48.1*	*IV*	*4.15*	....	*1800*	.....
	Nitrogen..	*Nitrogen*.....	*N*	*14.008*	*I to V*	.....	*.97*	*—210*	*—196*
		Phosphorus.....	*P*	*31.027*	*III-V*	*1.8*	....	*44*	*290*
		*Arsenic.....	As	74.96	III-V	5.7	....	850	449.5
		*Antimony.....	Sb	121.77	III-V	6.6	....	630	1460
		*Bismuth.....	Bi	209.00	III-V	9.7	....	271	1485
		Vanadium.....	*V*	*50.96*	*III-V*	*5.7*	....	*1720*	.....
		Oxygen	**O**	*16.000 (15.97)*	*II*	.....	*1.10*	*—218*	*—183*
		Hydrogen	**H**	*1.008 (1.)*	*I*	.....	*.07*	*—259*	*—252*

Very Rare Elements.

	Name	Symbol	Atomic Weight
51	Argon.....	A	39.91
52	Beryllium.....	Be	9.02
53	Caesium.....	Cs	132.81
54	Cerium.....	Ce	140.25
55	Columbium....	Cb	93.1
56	Dysprosium....	Dy	162.52
57	Erbium.....	Er	167.7
58	Europium.....	Eu	152.0
59	Gadolinium....	Gd	157.26
60	Germanium....	Ge	72.6
61	Hafnium.....	Hf	181.0
62	Helium.....	He	4.0
63	Holmium.....	Ho	163.4
64	Indium.....	In	114.8
65	Iridium.....	Ir	193.1
66	Krypton.....	Kr	82.9
67	Lanthanum....	La	138.9
68	Lutecium.....	Lu	175.0
69	Neodymium...	Nd	144.27
70	Neon.....	Ne	20.2
71	Niton.....	Nt	222.0
72	Osmium.....	Os	190.8
73	Praseodymium.	Pr	140.92
74	Polonium.....	Po	210.0(?)
75	Radium.....	Ra	225.95
76	Rubidium.....	Rb	85.44
77	Samarium.....	Sa	150.43
78	Tantalum.....	Ta	181.5
79	Terbium.....	Tb	159.2
80	Thorium.....	Th	232.15
81	Thulium.....	Tm	168.5
82	Uranium.....	U	238.17
83	Xenon.....	Xe	130.2
84	Ytterbium....	Yb	173.6
85	Yttrium.....	Yt	89.0
86	Zirconium.....	Zr	91.2

Electrons: Until 1900 all the elements had resisted all efforts to break them up into simpler substances, and atoms were considered to be the smallest divisions of matter. With the discovery of radium and other radio-active substances, however, a new field for investigation was opened, and subsequent discoveries indicate that the atom is divisible. These very small particles are called electrons. It is thought that electrons, in some intimate relation to the Ether, are the fundamental particles of which all matter is composed.

SECTION VI.

CHEMICAL FORMULA AND REACTIONS.

Chemical Formulas of Compounds: The method of representing the elements by symbols, together with the system of atomic weights, affords a convenient and concise method of representing chemical compounds, or to be more explicit, the molecules of chemical compounds. Thus, by analysis, water is found to be composed of hydrogen and oxygen in the proportion of eight parts of oxygen to one part of hydrogen by weight. These facts are completely expressed by the formula H_2O, which indicates a molecule of a compound composed of two atoms of hydrogen and one atom of oxygen, or, since the atomic weight of hydrogen is 1 and of oxygen, 16, 2 parts of hydrogen to 16 parts of oxygen (1 to 8). Likewise, the formula Fe_2O_3 represents a compound, the molecule of which is made up of 111.68 parts of iron to 48 parts of oxygen.

Molecules of Elements: In studying chemical changes in which elements are set free, it is found that they are much more active at the instant of their liberation than afterwards, and are, therefore, said to be in the **nascent state** at that instant. This fact leads to the belief that the instant an element is set free from its compounds it exists in the atomic condition, but if there is nothing else present with which the atoms can combine, they combine with each other to form molecules of the element. This idea cannot be proven in the case of solids, but its correctness is easily shown in the case of gases. From many facts, Avogadro was able to show **that equal volumes of all gases, under the same conditions of temperature and pressure, contain the same number of molecules.** Hence, the molecular weight in grams of all gases give a constant volume of 22.32 liters, called the gram-molecular volume. Now, the weight of 22.32 liters of oxygen=32 gms., of hydrogen, 2 gms., of nitrogen, 28 gms. Dividing these weights by the respective atomic weights of the elements, the quotient is 2 in each case. Hence, the molecules of these elements contain two atoms each, and the correct formulas for these elements are O_2, H_2 and N_2, respectively.

Chemical Equations: This system of symbols and weights also simplifies the representation of chemical changes. Suppose it is desired to represent the chemical change that takes place when a common substance, like coal, for instance, burns. Coal is largely made up of carbon; the element which combines with it is oxygen in the air; an invisible gas, CO_2, is

formed and diffuses into the air. This change, spoken of as a reaction, is represented in the form of an equation; thus, $C+O=CO_2$.

Balancing Reactions: Since matter is conserved, there must be as many atoms on one side of the equation as on the other. This is shown by placing a 2 before O on the left side of the equation, thus, $C+2O=CO_2$. This process is called balancing. Thus, reactions tell not only the names of the reacting substances and of the products formed, but also give the proportions by weight, and in the case of gases, volume relations as well.

Radicals: In the molecules of many chemical compounds, certain groups of atoms appear to be more closely bound together than others in the same molecule. In these groups the atoms composing them appear to bear a fixed relation to each other, which remains unchanged during a chemical reaction. Thus, in many wet reactions in which H_2SO_4 is employed as a reagent, the sulphur and oxygen do not separate but remain closely combined, as illustrated in the reaction that takes place between this acid and barium chloride:

$$H_2(SO_4)+Ba\,Cl_2=Ba(SO_4)+2\,HCl$$

Such groups of atoms are called radicals.

Ions and Electrolysis: In electrolytes these radicals are readily identified as ions. From a study of the effect of dissolved electrolytes on the boiling and freezing points of the water in which they are dissolved, and on their osmotic pressures, evidence is obtained to show that each of the dissolved molecules breaks up or dissociates into two or more parts.

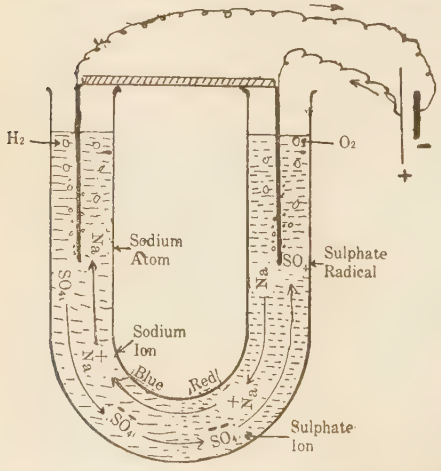


Fig. 2. Showing decomposition of water and formation of sodium hydroxide and sulphuric acid from sodium sulphate by electrolysis.

The following simple experiment may be employed to throw additional light upon this subject. Into the U-tube of Fig. 2 is placed a solution of sodium sulphate and some neutral litmus, into which is immersed two small platinum rods to act as electrodes for an electric current, as shown in the figure. Upon closing the circuit, bubbles of hydrogen are given off at the cathode and bubbles of oxygen at the anode, while the solution about the cathode becomes deep blue in color, showing it is basic, and that about the anode becomes red, showing it to be acid. These facts are explained by assuming that the molecules

of dissolved Na_2SO_4 dissociate into parts, called ions. This dissociation is indicated thus: $Na_2SO_4 = \overset{+}{Na} + \overset{+}{Na} + \overset{--}{SO_4}$. The sodium ions, $\overset{+}{Na}$, carrying a positive charge of electricity, are propelled by the current toward the cathode, while the negatively charged sulphions, $\overset{--}{SO_4}$, go to the anode. Here they give up their charges and become chemically active, decomposing the water thus:

$$2Na + 2H_2O = 2NaOH + H_2 \qquad 2SO_4 + 2H_2O = 2H_2SO_4 + O_2$$

This experiment is but one example of electrolysis. Any inorganic acid, base or salt may be substituted for the sodium sulphate; and any conductor of electricity, such as iron, may be used instead of platinum. It is to be noted, however, that if iron had been used in this experiment, the anode would have been corroded away by the acid radical; thus, $Fe + SO_4 = FeSO_4$. Electrolysis has been advanced to explain the corrosion of iron.

Dry and Wet Chemistry: Chemical changes take place under constant conditions. Substances that will react in one way under one set of conditions will not react, or react in an entirely different way, under another set of conditions. Some substances react simply by contact, as quick lime and water. Many reactions will take place only in a water solution, while many other substances, being insoluble in water, must be heated almost to their point of fusion before they react. A study of reactions between substances in solution is called "wet chemistry" while the study of reactions brought about by heat is termed "dry chemistry." However, under the same conditions, the same substances will always produce the same results. This fact is known as the law of constancy of nature.

Acids, Bases and Salts of Dry Chemistry: Most substances dealt with in wet chemistry lose water when heated. This statement is particularly true of inorganic acids, bases and salts. Thus, in the case of acids and bases, heat breaks up these compounds into water and oxides, called **anhydrides.** Acids give **acid anhydrides**, and bases, **basic anhydrides.** These anhydrides constitute the acids and bases of dry chemistry. They have the same power of neutralization that their corresponding wet compounds possess, and form neutral compounds to which the term **slag** is applied instead of **salt.** Many salts, in crystallizing from aqueous solutions, unite with, or better, take up a definite amount of water, which does not go to form a new compound, but to form crystals, and is called, therefore, **water of crystallization.** This water is held very loosely by the molecule and is readily given up by it. In some crystals, like those of washing soda, for example, this tendency is so pronounced that they give up their water of crystallization to the air, if its humidity is low. Such substances are said to be **efflorescent.** On the other hand, many dry substances absorb moisture from the air and are, therefore, said to be

hygroscopic. A few substances will absorb enough water from a very moist air to become wet and actually go into solution in the water they absorb. These substances are said to be **deliquescent.** The following reactions will serve to illustrate these facts in so far as they involve chemical changes:

$$H_2SiO_3 + \text{heat} = H_2O + SiO_2$$

Metasilicic Acid Water Silica, or silicic anhydride

$$Mg(OH)_2 + \text{heat} = H_2O + MgO$$

Magnesium hydroxide Magnesia—a basic anhydride

$$Na_2SO_4 \cdot 10H_2O + \text{heat} = 10H_2O + Na_2SO_4$$

Glauber Salt (Crystallized) Sodium Sulphate (Dry Powder)

In this connection a study of the following table will also prove helpful.

Table 2. Acids, Bases and their Anhydrides with Salts Resulting from Neutralization.

Name of Compound	Formula of Compound	Formula of Anhydride	Salt With		
			Univalent Base	Divalent Base	Trivalent Base
Sodium hydroxide	NaOH	Na_2O			
Calcium hydroxide	$Ca(OH)_2$	CaO			
Ferric hydroxide	$Fe(OH)_3$	Fe_2O_3			
Sulphuric Acid	H_2SO_4 or $H_2O \cdot SO_3$	SO_3	$Na_2O \cdot SO_3$ or Na_2SO_4	$CaO \cdot SO_3$ or $CaSO_4$	$(Fe_2O_3) \cdot (SO_3)_3$ or $Fe_2(SO_4)_3$
Nitric Acid	HNO_3 or $H_2O \cdot N_2O_5$	N_2O_5	$Na_2O \cdot N_2O_5$ or $NaNO_3$	$CaO \cdot N_2O_5$ or $Ca(NO_3)_2$	$Fe_2O_3 \cdot (N_2O_5)_3$ or $Fe(NO_3)_3$
Orthophosphoric Acid	H_3PO_4 or $3H_2O \cdot P_2O_5$	P_2O_5	$3Na_2O \cdot P_2O_5$ or Na_3PO_4	$(CaO)_3 \cdot P_2O_5$ or $Ca_3(PO_4)_2$	$Fe_2O_3 \cdot P_2O_5$ or $FePO_4$
Orthosilicic Acid	H_4SiO_4 or $2H_2O \cdot SiO_2$	SiO_2	$2Na_2O \cdot SiO_2$ or Na_4SiO_4	$(CaO)_2 \cdot SiO_2$ or Ca_2SiO_4	$(Fe_2O_3)_2 \cdot (SiO_2)_3$ or $Fe_4(SiO_4)_3$

Kinds of Reactions: As already indicated, all reactions may be placed under one of two heads; namely, those that liberate heat, called exothermic, and those that absorb heat, called endothermic. A more detailed classification, such as the following, is sometimes employed:

1. Direct combination (synthesis)—$2H + O = H_2O$ or $2H_2 + O_2 = 2H_2O$.
2. Direct decomposition (analysis)—$2HgO = 2Hg + O_2$.
3. Simple replacement or substitution—$2H_2O + 2Na = 2NaOH + H_2$.
4. Double replacement or metathesis—$BaCl_2 + H_2SO_4 = BaSO_4 + 2HCl$.
5. Oxidation—$\begin{cases} 3\,Fe + 4O = Fe_3O_4. \\ Fe\,Cl_2 + Cl = Fe\,Cl_3. \end{cases}$
6. Reduction—$\begin{cases} Fe_3O_4 + 8H = 3\,Fe + 4H_2O. \\ Fe\,Cl_3 + H = Fe\,Cl_2 + HCl. \end{cases}$

The two processes of oxidation and reduction are of great importance in metallurgy. They have a triple meaning. Primarily, oxidation means the taking on of oxygen by an element or compound, and reduction means the giving up of oxygen. In the case of elements that form more than one

compound, if the number of atoms of one that combines with a fixed number of the other be increased, the process is oxidation; if decreased, reduction. In metallurgy an element in the metallic state is said to be reduced. The two processes are inseparable; when one thing is reduced, another is oxidized. In metallurgical operations these two processes are of paramount importance, for all the substances reduced constitute the metallic product and all in oxidized form make up the slag.

Some Laws Controlling Chemical Reactions: In writing reactions considerable knowledge of a specific character is essential. Thus, suppose it is required to write the reaction that represents the action of iron brought in contact with water. First, it will be necessary to know under what conditions the substances are brought together, for at ordinary temperatures no reaction will take place. At a high temperature, a reaction takes place, and it is necessary to know that ferroso-ferric oxide and hydrogen are produced, and the formulas of all these substances. This knowledge can then be indicated thus: $Fe+H_2O=Fe_3O_4+H_2$. Balancing the reaction, which is done by inspection and arithmetic, is the next step. Finally, the reaction is reversible, for if instead of steam over hot iron, hydrogen be passed over hot iron oxide, iron and water are the products. The reaction is, therefore, correctly written thus: $Fe_3O_4+4H_2 \rightleftharpoons 3Fe+4H_2O$, or $3Fe+4H_2O \rightleftharpoons Fe_3O_4+4H_2$. Many reversible reactions, under conditions which do not permit the products to escape from the field of action, do not proceed to completion, but reach a balanced condition after a time and seem to stop, though as a matter of fact they are progressing in one direction as rapidly as in the other, hence are described as being in dynamic equilibrium. In practical chemical work it is usually desirable to have reactions go to an end. As an aid in writing reactions the following laws may be found of value:

A. The reaction of two or more substances will go to an end, that is, will be complete, provided,

1. One of the products is volatile at the temperature of the reaction.
2. One of the products is insoluble in the solvent in which the reaction takes place.
3. One of the products is a non-electrolyte, that is, does not ionize in the solvent.

B. The speed of a chemical action in a given direction may be increased by effecting a greater concentration of one of the reacting substances. This is a simple, non-mathematical statement of the law of mass action.

C. Chemical reactions always tend to proceed in the direction that will liberate the most heat, and without the addition of heat from an external source those substances that have the greatest heats of formation will tend to form.

SECTION VII.

CHEMICAL NOMENCLATURE.

General Principle: A brief description of the nomenclature of chemical compounds will be found of great assistance to those not familiar with the subject. The names of the elements first discovered, and, therefore, unfortunately, the more common ones, are not based on any principle; but of the more recently discovered elements the metals have received names ending in **um** or **ium,** and the metalloids, in **n** or **ne.** In the naming of compounds, however, the old names have been discarded and new ones substituted. The system employed in assigning these new names is this: **The name of a compound should show the elements of which it is composed, and as far as possible their relative proportions.**

Terminology of Binary Compounds: The simplest compounds are those composed of only two elements. The names of all such compounds are made up of the name of the basic element, if one is present, succeeded by the name of the acid element, which ends in **ide:** Examples; ferrous (iron) sulphide, FeS; sodium chloride, NaCl; calcium oxide, CaO.

In such cases as iron and sulphur, where the same two elements combine to form more than one compound, the compounds, when two in number, are distinguished by changing the ending of the metallic part of the name from **ous** to **ic;** thus, ferrous sulphide, FeS; ferric sulphide, Fe_2S_3; stannous chloride, $SnCl_2$; stannic chloride, $SnCl_4$. Often, the prefixes **mono-, di-, tri-, tetra-, pent-, per** are used, especially if the name will not permit the ending **ous** and **ic,** or if more than two compounds are formed by the same two elements. Carbon dioxide, CO_2; nitrous oxide, or nitrogen monoxide, N_2O; nitric oxide or nitrogen dioxide, N_2O_2; (NO); nitrogen trioxide, N_2O_3; nitrogen tetroxide or nitrogen peroxide, N_2O_4; nitrogen pentoxide, N_2O_5 are examples.

Terminology of Ternary Compounds: The names of compounds that contain three elements, provided they are not derived from acids, may end in **ide,** also, in which case all three of the elements appear in the name, as sodium aluminum fluoride, (Na_3AlF_6), bismuth oxychloride, (BiOCl). A few ternary compounds derived from **ic** acids have names ending in **ate,** as potassium chlorplatinate, (K_2PtCl_6).

Terminology of Acids: Acids are composed of the acid-forming elements in combination with hydrogen or with hydrogen and oxygen. The name of a given acid is derived from the name of the acid forming element. The best known acid of an element has the ending **ic.** Example, chloric acid, $HClO_3$. Then the acid, the molecule of which contains one less atom of oxygen, has the ending **ous.** Example, chlor**ous** acid, $HClO_2$. If the element also forms an acid containing one more atom of oxygen in its molecule than the **ic** acid, it is designated by the prefix **per.** Example,

perchloric acid, $HClO_4$. Acids, like sulphuric (H_2SO_4) and ortho phosphoric (H_3PO_4), which contain more than one replacable hydrogen atom are called, as a class, polybasic acids; and, in individual cases, the different acids are referred to as **di basic, tri basic,** etc., because such acids may be neutralized by more than one base at once. For example, potassium and sodium may replace the two hydrogens in H_2SO_4 to form sodium potassium sulphate, $NaKSO_4$. In all such double salts both the base forming elements must appear in the name of the salt.

Terminology of Bases: The base forming elements form compounds with hydrogen and oxygen in which these two elements appear as a radical, OH, called hydroxyl. Hence, these compounds are called hydroxides in wet chemistry. Thus, sodium hydroxide, Na OH, and calcium hydroxide Ca $(OH)_2$ are examples. In dry chemistry the hydrogen and part of the oxygen are driven off, leaving the oxides which still act as acids and bases.

Terminology of Salts: Salts take their names from those of the base forming elements and the acids of which they are composed, changing the endings of the acids. Salts of acids that end in **ic** change this ending to **ate,** and those that end in **ous,** to **ite.** Thus, sodium chlorate, $NaClO_3$, derived from chloric acid, sodium perchlorate, $NaClO_4$, from perchloric acid, and sodium chlorite, $NaClO_2$, from chlorous acid, are examples. Other systems of nomenclature are in use, but the ones just noted cover the largest field.

SECTION VIII.

CHEMICAL CALCULATIONS.

Kinds of Problems: Chemical calculations constitute a very important branch of study in the training of the metallurgist. They are of three general classes; namely, those involving weight, those involving the volumes of gases, and those involving both weight and volume. Further subdivisions of these classes may be made, the principles of which are best taught from specific examples, as follows:

PROBLEMS INVOLVING WEIGHT ONLY.

Calculation of the Molecular Weight from the Formula: Problem: The formula of copper sulphate is $CuSO_4$. Find its molecular weight. Solution: From the table of atomic weights and the formula, we find

Atomic weight of copper =63.57
" " " sulphur=32.06
" " " oxygen =16

Atomic Weights		No. of Atoms		Combining Weights
63.57	x	1	=	63.57
32.06	x	1	=	32.06
16.	x	4	=	64.00

Molecular weight of $CuSO_4$= 159.63 Ans.

Calculation of Percentage Composition of a Compound from its Formula: Problem: Find the percentage composition of a compound, the formula of which is $CuSO_4$.

Solution:

	Cu	S	O_4	
Molecular weight=63.57+32.06+(4 x 16)=159.63.				
159.63	63.57	32.06	64.00	

Percentage Composition=39.83% Copper, 20.09% Sulphur, 40.09% Oxygen. Ans.

Calculation of Formula from the Analysis of a Compound: Problem: By analysis a pure compound is found to be composed of calcium 29.41%, sulphur 23.53% and oxygen 47.06%. What is its simplest formula?

Solution:

Element		Parts in a Hundred		Atomic Weights	Atomic Ratios	Number of Atoms
Ca	—	29.41	÷	40.07	= .735— ÷.735=	1 Ca
S	—	23.53	÷	32.06	= .735+ ÷.735=	1 S
O	—	47.06	÷	16.	=2.941— ÷.735=	4 O

Formula of compound is $CaSO_4$. Ans.

Calculation of Relative Weights from the Chemical Equation: Problem: Five per cent. of a certain limestone is non-volatile impurities and 95% is pure calcium carbonate. What will be the weight of lime obtained from calcining 2000 lbs. of this stone?

Solution:

Weight of impurities =5% of 2000= 100 lbs.
" " calcium carbonate =1900 lbs.

Reaction on calcining.....	$CaCO_3$		=CaO+	CO_2
Combining or atomic wts..	40.00+12+(3x16)=	40.+16+	12+(2x16)	
Relative or molecular wts..	100.00	= 56.00	+	44

100 lbs. $CaCO_3$ gives 56 lbs. CaO
1 " " " .56 " "
1900 " " " 1064 " "

1064 lbs. CaO+100 lbs. non-volatile impurities=1164 lbs. of lime. Ans.

PROBLEMS INVOLVING VOLUME ONLY.

Calculation of Relative Volumes of Gases: From Avogadro's hypothesis, it is known that molecular weights of all gases give the same volume under standard conditions of 0°C and 760 mm. barometric pressure. Problems involving volumes of gases only are, therefore, very simple to solve, because the relative volumes are identical with the coefficients of

the molecules, as will be evident from an inspection of the following examples:

$H_2+Cl_2=2HCl$

1 vol. hydrogen+1 vol. chlorine gives 2 volumes hydrochloric acid gas

$CH_4+2O_2=CO_2+2H_2O$

1 vol. methane+2 vol. oxygen gives 1 vol. carbon dioxide+2 vol. water vapor

$N_2O_2+O_2=2NO_2$

1 vol. nitric oxide+1 vol. oxygen gives 2 volumes nitrogen peroxide.

PROBLEMS INVOLVING BOTH WEIGHT AND VOLUME.

Indirect Method: This method necessitates finding the relative weights of the gases involved, from which the volumes may be calculated from the specific gravity, or the weight of a unit volume.

Problem: How many cubic feet of carbon dioxide measured under standard conditions would be given off by 2000 lbs. pure calcium carbonate during the process of calcination?

Solution:

Reaction $CaCO_3 = CaO + CO_2$

$$\frac{40+12+48}{100} = \frac{40+16}{56} + \frac{12+2x16}{44}$$

100 lbs. $CaCO_3$ give 44 lbs. CO_2
2000 " " " 880 " CO_2
Wt. 1 cu. ft. CO_2=.1235—lbs.
880÷.1235 = 7125—cu. ft. Ans.

Direct Method: The fact that molecular weights of gases give constant volumes at standard conditions affords a simple direct method for calculating volumes from the equation. If the weights are expressed in grams, each gram-molecule of the gases involved represents 22.32 –liters; if in kilograms, each kilogram-molecule stands for 22.32—cubic meters; and if in avoirdupois ounces, each ounce-molecule gives a volume of 22.32 + cubic feet. By this method the problem above would be solved as follows:

2000 lbs.=32000 ozs.

? cu. ft.

$CaCO_3 = CaO + CO_2$

$$\frac{40+12+(3x16)}{100} = \frac{40+16}{56} + 22.32 \text{ cu. ft.}$$

100 ozs. $CaCO_3$ gives 22.32 cu. ft.
1 " " " .2232—
32000 " " " 7142 —cu ft. Ans.

SECTION IX.

A DESCRIPTION OF ELEMENTS COMMONLY MET WITH IN THE MANUFACTURE OF STEEL.

Oxygen.

Occurrence: This element is most widely distributed in nature; 49.85 per cent. of the solid crust of the earth, 88.89 per cent. of water and 20.8 per cent. of air is oxygen. In air it exists in a free state. In a combined state, it exists in limestone, sand, marble, clay, quartz, iron ore, and many other substances.

Preparation: It is prepared by merely heating certain of its compounds, some of which are mercuric oxide, potassium chlorate and manganese dioxide; by the decomposition of water by electrolysis; and from the air by purifying processes.

Properties: Oxygen is a colorless, odorless, tasteless gas, heavier than air (sp. gr.=1.1056) and slightly soluble in water. At a low temperature and a high pressure it is converted into a liquid which boils at—181°C.

The phenomenon of ordinary burning or combustion is due to the combination of oxygen with other substances. It unites with many elements to form a class of compounds, the oxides. It is necessary to life. Animals die in an atmosphere of less than 16 per cent. oxygen.

Compounds: Some important oxides are: carbon dioxide, CO_2, carbon monoxide, CO, calcium oxide, CaO, magnesium oxide, MgO, ferric oxide, Fe_2O_3, and ferroso-ferric oxide, Fe_3O_4. The last two are important as ores of iron.

Hydrogen.

Occurrence: Hydrogen does not occur in nature in a free state, but combined with oxygen it forms water, of which it constitutes 11.11 per cent. In a combined state it occurs also in the bodies of plants and animals, hence, in the volatile matter of coal, in petroleum, and in natural gas of which it constitutes almost 25 per cent. Water is always one of the products of combustion when a fuel containing hydrogen is burned.

Preparation: It can be prepared by decomposing water with sodium, potassium, hot iron, hot coke, or the electric current; by treating certain metals with certain acids; and by treating aluminum with sodium or potassium hydroxide.

Properties: Hydrogen is a colorless, tasteless, odorless gas, almost insoluble in water. It can be converted into a liquid that boils at—252°C. It is the lightest substance known, being about $\frac{1}{15}$ as heavy as air and $\frac{1}{16}$ as heavy as oxygen. Its specific gravity, air standard, is .0696. It is combustible and explosive. It combines with oxygen in the proportion of 1:8 to form water. Its great tendency to combine with oxygen makes it an intense reducing agent.

Sulphur.

Occurrence: This element occurs free in the neighborhood of volcanoes and in underground deposits, from which it may be prepared by purifying processes. In combined state it is found as FeS_2, $FeCuS_2$, ZnS, and PbS, the last three being valuable ores of copper, zinc, lead, respectively. It also occurs as the sulphates $CaSO_4$, $BaSO_4$ and $PbSO_4$, and in animal and vegetable matter. Compounds of sulphur occur in iron ores, in limestone, and in coal; and these are reduced in the blast furnace, when a varying part of the sulphur combines with the iron, in which form it is very undesirable, if present in large amounts, on account of its injurious effects on steel and cast iron.

Properties: Sulphur is a brittle, yellow crystalline solid which melts at 114.5°, forming a straw colored liquid. It is allotropic, i. e., can exist in different physical forms. These forms are prismatic, rhombic and amorphous. When heated to a sufficiently high temperature, it combines with oxygen to form sulphur dioxide, SO_2, with iron to form ferrous sulphide, FeS, and with most of the metals, forming sulphides. The sulphur in iron or steel is in the forms of FeS and MnS, distributed almost uniformly throughout the metal while in the molten state. Upon solidifying, however, owing to the difference in density and fusion temperature between these compounds and the metal, they may, under normal conditions, segregate to some extent, causing some parts of the solidified mass to show a higher content of this impurity than the average, or of the whole in the molten state. With hydrogen it forms a gas, hydrogen sulphide, H_2S,—very important in Chemistry.

Uses: Sulphur is used in the manufacture of matches and black gun powder, also for disinfecting purposes and for vulcanizing rubber. Its chief use, however, is in the manufacture of sulphuric acid; and the amount of this acid consumed by a nation is a measure of its scientific advancement.

Compounds: Besides compounds already mentioned, sulphur forms several acids, one of which, sulphuric acid, $H_2O \cdot SO_3$ (H_2SO_4) is a most important compound. It is obtained by oxidizing sulphur dioxide, SO_2, which is given off as a gas from the roasting of FeS_2, ZnS, CuS, and from the burning of sulphur.

Carbon.

Occurrence: This element occurs free in nature in crystalline forms as diamonds and graphite and in the amorphous form as coal. It is the chief constituent of the bodies of plants and animals, of all natural fuels, and of nearly all prepared fuels. It occurs in combined state in limestone, magnesite, marble and other carbonate rocks.

Properties: Carbon is allotropic; diamond and graphite have been mentioned. The common amorphous forms are coal, lampblack, charcoal, coke, bone black and gas carbon. Its density varies with its form.

Compounds and Uses: Carbon forms many compounds with hydrogen, called hydrocarbons, as methane CH_4, ethylene C_2H_4, benzene C_6H_6, acetylene C_2H_2, each of which is but the first member of a series of related compounds. With oxygen it forms carbon dioxide, CO_2 which is a product of combustion and of respiration. CO_2 is also given off when carbonates, such as limestone, are heated. The reaction is, $CaCO_3 = CaO + CO_2$. Carbon monoxide is formed in combustion when the supply of oxygen is insufficient for the formation of CO_2. Thus, in the blast furnace, a fixed amount of air is blown against an excess of hot carbon, which act results in this reaction: $2C + O_2 = 2CO$. Owing to its tendency to combine with oxygen, forming CO_2, CO is a good reducing agent. So, the CO formed before the tuyeres of the blast furnace reacts with the iron oxide thus:

$$3CO + Fe_2O_3 = 3CO_2 + 2Fe.$$

Carbon alone acts as a reducing agent in the metallurgy of iron.

$$3C + Fe_2O_3 = 2Fe + 3CO.$$

Iron forms a carbide with carbon, the formula of which is Fe_3C. In pig iron it is also found uncombined in the form of tiny flakes of graphite, hence the term graphitic carbon. Carbon has a marked effect upon iron. The varying properties of steel and the many uses to which it can be applied are due largely to the influence of this element. Carbon in steel, then, up to a certain limit, is not to be considered as an impurity but as an essential factor.

Silicon.

Occurrence: Next to oxygen, silicon is the most abundant element in nature. It is the most important constituent of the mineral part of the earth. Sea sand, quartz, jasper, opal and infusorial earths are almost pure forms of SiO_2. As silicates, it occurs in clay, mica, talc, hornblend and feldspar. On account of its wide distribution it forms the chief impurity of iron ore, as well as of nearly all natural mineral deposits.

Compounds: As already indicated silica, SiO_2, is one of the chief compounds of silicon. It also forms several acids, chief of which is silicic acid, $2H_2O.SiO_2$ (H_4SiO_4) which loses water when heated and forms SiO_2.

$$H_4SiO_4 = SiO_2 + 2H_2O.$$

Thus, in whatever form silicon may occur in an ore, it is looked upon as SiO_2. This substance is the great acid of dry chemistry and at high temperatures will neutralize any base with which it comes in contact. In the blast furnace some of the silica (SiO_2) contained in the charge is reduced to silicon. The amount so reduced varies with the working conditions of the the furnace, mainly the temperature. Once reduced, the silicon alloys with the iron and becomes a part of the metallic bath. All but traces of this silicon is re-oxidized and removed in the various processes of making steel. However, a little is beneficial to steel, so it is sometimes added in small amounts in the form of an iron alloy.

Nitrogen.

Occurrence and Properties: This element occurs in niter beds as saltpeter, KNO_3, and Chili saltpeter, $NaNO_3$, also in organic compounds and in coal. It is an odorless, tasteless, colorless gas that constitutes about 78 per cent. of the atmosphere.

Compounds: With hydrogen it forms ammonia, NH_3; with oxygen a series of oxides, N_2O, NO, N_2O_3, N_2O_4 and N_2O_5; and with hydrogen and oxygen, an important acid, $H_2O{\cdot}N_2O_5$ (HNO_3). It is a very inert element and has very slight effects in the manufacture of steel. Nevertheless, its presence in the air in so large amounts makes it an important factor in blast furnace practice.

Phosphorus.

Occurrence: Phosphorus, always combined with other elements, occurs widely distributed in limited amounts, particularly in soils. It is, therefore, found in all iron ores. It occurs in deposits as phosphorite and apatite, and is an important constituent of bone.

Properties and Compounds: While phosphorus belongs in the same group of elements as nitrogen, it does not much resemble it from a physical standpoint. It is allotropic and exists in two forms, as a pale yellow solid that melts readily at the low temperature of 44.1°C, and as a red form quite different in properties. While it is a much more active element, it closely resembles nitrogen chemically. It forms compounds with hydrogen and oxygen, such as PH_3 and P_2O_5, and an acid, $H_2O.P_2O_5$ (HPO_3), called metaphosphoric acid. It generally is found in nature as salts of orthophosphoric, $3H_2O.P_2O_5$ (H_3PO_4), and pyrophosphoric, $2H_2O.P_2O_5$ ($H_4P_2O_7$), acids. With iron it forms a phosphide, Fe_3P. It is completely reduced in the blast furnace, hence all the phosphorus occurring in the raw materials is found in the pig iron. In steel it is a very undesirable impurity, but fortunately it is oxidized readily, when it can be neutralized with lime and easily removed as part of a slag.

Calcium and Magnesium.

While these two elements belong to different groups, they are very similar so far as the manufacture of iron and steel are concerned. With few exceptions one may be substituted for the other without great inconvenience. Their oxides are the more important bases of dry chemistry.

Occurrence and Chief Compounds: Both elements occur as insoluble carbonates; limestone, marble, chalk and marl are forms of calcium carbonate, $CaO.CO_2$ ($CaCO_3$). Magnesite is magnesium carbonate, $MgCO_3$. When heated, both these compounds decompose into the oxides and carbon dioxide, thus:

$$CaCO_3 = CaO + CO_2.$$
$$MgCO_3 = MgO + CO_2.$$

CaO represents quick lime, and MgO, magnesia.

These elements also occur together as a double salt of carbonic acid, calcium magnesium carbonate, $CaMg(CO_3)_2$, commonly called **dolomite**, which gives calcium magnesium oxide $CaO \cdot MgO$ when calcined.

$$CaMg(CO_3)_2 = CaO \cdot MgO + 2CO_2.$$

Uses of Lime and Magnesia: Lime, CaO, Magnesia, MgO, and the double oxide, $CaO \cdot MgO$, are all very refractory. But on account of its tendency to slake in air, CaO is not used as such. Practically, MgO is the best basic refractory known, and calcined dolomite is the best available substitute.

The oxides are reduced with difficulty, and on account of their cheapness constitute the principal basic fluxes. As MgO is the leading basic refractory, CaO is the leading basic flux. It combines with both silica and phosphoric acid to form readily fusible slags, which have a lower density than iron and consequently lie upon the surface of the metallic bath.

Aluminum.

Occurrence and Properties: This element in combined form is very widely distributed, occurring as one of the constituents of feldspar, granite, mica, cryolite, and all clays. It is reduced from the oxide, Al_2O_3, by an electrolytic process, in which state it is applied to many uses. It has a strong affinity for oxygen, violently reducing iron oxide, and on this account it is added to steel as a deoxidizing agent.

Compounds: In its compounds aluminum displays decidedly basic properties, forming salts with all the common acids except carbonic acid. In wet reactions, it forms neither a carbonate nor a sulphide, but it readily combines with sulphur at high temperatures. Aluminum hydroxide, $Al(OH)_3$, however, acts like both an acid and a base. When this compound is heated, it loses water and forms alumina, Al_2O_3. It is found in varying amounts in all the raw materials that enter into the metallurgy of iron. In the blast furnace it is never reduced. Its presence, however, has a marked influence on the slag, affecting its fluidity and fusion temperature, important considerations in blast furnace practice. In its purer states alumina is a good refractory, but its scarcity prohibits its extensive use as such.

Chromium.

Occurrence: This element is somewhat rare. In small deposits it is found as chromite, $Cr_2O_3 \cdot FeO$. This substance is the best neutral refractory known. In its purer states it melts at about 2175°C.

Properties and Uses: Chromium is both acid and basic in character. It is very important in the manufacture of alloy, or special steels. Its chief effect is one of hardening, hence it is employed to increase the hardness of projectiles, armor plate, automobile steel, and tool steels.

Manganese.

Occurrence: This element occurs in nature as MnO_2, its deposits being somewhat limited in the United States. In very small amounts it is widely distributed, and is found in nearly all raw materials of iron manufacture. About 75 per cent. of this manganese is reduced in the blast furnace, so it is a constituent of all pig iron. But it is readily oxidized in the purifying processes, and except for almost traces, that found in steel is added to it in the process of manufacture. Its effect in steel is good, because, in carbon steel, it offsets the evil effects of oxygen and sulphur. Higher percentages, 7 per cent. to 15 per cent., are employed to produce the special steel known as manganese steel.

Iron.

Occurrence: This most important metal occurs in combined states and, in slight amounts, in nearly all earthy matter, as clays, soils, sands, etc. In deposits, it is found as the sulphide, FeS_2, as silicates, as a constituent of chromite, as the carbonate, $FeCO_3$, and as the oxides, Fe_2O_3 and Fe_3O_4. The compound last named is magnetic.

Properties: Pure iron, which is now produced electrolytically from ore or pig iron in fairly large quantities, is somewhat unlike the ordinary commercial forms. It is grayish-white in color and relatively soft when compared with steel of high carbon content. It is malleable, ductile, and magnetic. Its specific gravity is 7.78, and its melting point in its purest commercial form is about 1520 °C. The presence of certain elements, notably carbon, silicon, phosphorus or sulphur, in the metal lowers the melting point rapidly.

Compounds: Iron forms two series of compounds, the ferrous and the ferric. The more important ferrous compounds are FeO, $Fe(OH)_2$, $FeCl_2$, $FeSO_4 \cdot 7H_2O$; corresponding ferric compounds are Fe_2O_3, $Fe(OH)_3$, $FeCl_3$, $Fe_2(SO_4)_3$. Most of these compounds are of the highest commercial importance, and many will receive much fuller treatment as this course advances.

CHAPTER II.

REFRACTORIES.

SECTION I.

NATURE OF REFRACTORIES.

Importance: The problem of obtaining refractories suitable for each particular operation is one of supreme importance in the metallurgical arts, especially in the manufacture of steel. They form the chief materials of which all furnaces and retaining vessels are made, as well as flues and stacks through which hot gases are conducted. This equipment is expensive, and any failure in the refractories results in a great loss of time, equipment and product, and, too often, in loss of life as well.

Requirements of Refractories: A refractory may be defined as any substance which is infusible at the highest temperature it may be required to withstand in service. In any particular application however, this definition is incomplete, because the fact that a substance is infusible does not alone determine its value as a refractory. An almost infusible brick, for example, may be so fragile as to be worthless, since bricks are generally required to support a load in addition to resisting the effects of great heat. A perfect refractory would meet the following requirements at any temperature: (1) it would not fuse or soften; (2), it would not crumble or crack; (3), its contraction and expansion would be the minimum; (4), it would not conduct heat; (5), it would be impermeable to gases and liquids; (6), it would resist mechanical abrasion; (7), it would not react chemically with substances in contact with it. Needless to say, an absolutely perfect refractory has never been discovered. However, there are a number of substances which closely approach the first six requirements, at temperatures commonly employed in metallurgical work, and whether or not they will meet the seventh depends upon their chemical composition and the nature of the substances with which they are in contact.

Classes of Refractories: Refractory substances, in common with matter in general, are of three classes: namely, acid, basic and neutral. Recalling the chemical action of acids and bases toward each other, it is at once apparent that a refractory of an acid character is useless in contact with a basic slag, and vice versa. In selecting a refractory for a specific purpose, the first question to be decided is what class of refractory will be required. Other factors affecting its life and usefulness are the amount of impurities it contains and the uniformity of its composition; and, in the case of brick,

to these will be added strength, toughness, porosity, or other special qualities. In the manufacture of prepared refractories these factors are all under control, depending upon the selection of materials and the method of manufacture.

SECTION II.

ACID REFRACTORIES.

Chemical Composition: Acid refractories owe their acid character only to silica, SiO_2, and are of two kinds, namely, those composed mainly of silica and those composed of aluminum silicate, or clay. In the pure state silica fuses at a very high temperature, about 1830° C, a temperature much above that obtained in ordinary furnaces, but when heated in contact with basic substances it forms silicates, some of which are easily fused. Hence, in refractories composed of silica the presence of impurities, alumina as well as the stronger bases, must be guarded against. As a refractory, silica is used in the natural forms of sand and cut stone and in the prepared form of brick. Sand (90%to 99.5% SiO_2) is used to make up the bottoms of acid open hearth furnaces and of some types of heating furnaces. Ganister, a very superior material for lining converters, is a highly silicious rock. It has a silica content of about 98 per cent.

Silica Bricks are prepared from quartzite rock found in Pennsylvania, Wisconsin and Alabama. The rock is first crushed fine, then intimately mixed with a binding material which acts as a cement to hold the particles of silica together and to give the brick the necessary strength. For this purpose either clay or lime, usually in the form of milk of lime, is used, the former to produce quartzite brick and the latter, "silica" or ganister brick. The mixture, in a moist condition, is next compressed and moulded into the shape desired for the bricks, which are allowed to dry slowly and then are burned at high temperatures, about 1500° C., in large kilns. From seven to ten days are required to complete the burning. Silica brick expands slightly when heated.

Clay is a naturally occurring earthy material which has the property of plasticity when wet but becomes hard when burned. The ordinary varieties are more or less impure silicates of aluminum, formed by the decomposition, or weathering, of feldspathic rock, and contain high percentages (10% to 15%) of combined water. They may be residual or sedimentary. Fire clays are of two varieties, known as plastic and flint clays; the latter is very hard, even when ground, but very refractory. The most refractory clays are associated with the coal measures of Pennsylvania.

The impurities in clays are alkalies, due to undecomposed feldspar; sand; gravel; iron oxide, silicate or sulphide; calcium and magnesium silicates or carbonates; titania; and organic matter. Of these impurities,

the basic oxides are the most harmful, as they lower the fusion point decidedly. This is due to the fact that aluminum silicate combines with bases, forming double silicates.

The Process of Making Fire Clay Brick is similar to that for silica brick. The clay, in a finely crushed condition, is moistened with a definite amount of water and thoroughly mixed. When flint clay is being used, some plastic clay is used as a binder. Upon being dried, clay begins to shrink and continues to do so during the burning, when the combined water is driven off and the brick becomes hard. Thus, a brick, 9 inches in length after being burned, may measure from 9½ to 9¾ inches when moulded, depending on the mixture used. Calcined, or burnt, clay is employed in the mixtures to control the shrinkage. Once burned, the brick ceases to shrink and permanently loses the property of plasticity, which latter fact would indicate that the plasticity is due to combined water. The refractory properties of a brick depend upon the nature and amount of impurities and the ratio of silica to alumina. Besides its use as brick, clay is important as a refractory mortar to be used in laying bricks in furnaces and ladles, and as plaster where seamless linings are required.

SECTION III.

BASIC REFRACTORIES.

Magnesia, with a melting point of 2165°C is, for practical purposes, the most satisfactory basic refractory. It is prepared by calcining the mineral magnesite, a natural carbonate of magnesium. Large deposits are somewhat rare. Up to the outbreak of the World War the entire supply was obtained from Austria and Hungary. During the war, sources of supply were developed in the State of Washington, U. S. A., and the Province of Quebec, Canada, but the material is now being imported again. For this reason it is an expensive material, which fact accounts for its not being used except where a basic substance of the highest refractoriness is required. It makes an ideal brick for the construction of basic furnaces, and is used for the inner courses of bottoms and walls to slightly above the slag line. In a coarsely crushed form, described as pea size, it is very desirable material for making up bottoms in basic furnaces, as, mixed with a small percentage of basic cinder, it is readily fritted, forming a solid mass that resists chemical and mechanical action of the charge and the buoyant force of the bath. Magnesite mixed with about one per cent. of iron oxide and sintered in an electric furnace forms a very refractory substance, melting at about 2600° C. In granular form, this material can be used for furnace lining.

Lime is even more refractory than magnesia, resisting the intense heat of the oxyhydrogen flame, but on account of its slaking properties it is of little practical value as a refractory. Mixed with magnesia it gives fairly satisfactory results, if used properly.

Dolomite furnishes such a mixture and occurs in this country in abundant quantities. Prepared refractories composed largely or wholly of dead burned dolomite are manufactured under various trade names and have been extensively used as cheaper substitutes for magnesite. Dead burned dolomite cannot be fritted on bottoms as well as magnesite, and its lime content fastens upon it a tendency to form slag in basic steel furnaces. In the steel industry it is used chiefly for making up the banks of basic open hearth furnaces.

Bauxite is a natural form of the sesquioxide of aluminum, mixed with varying amounts of earthy matter and the corresponding oxide of iron. It usually contains one per cent. or more of titania, TiO_2. It is but feebly basic and, when free from silica, is highly refractory. In pure form alumina melts at 2010°C., but the fusion temperature of the natural bauxite will seldom exceed 1820°C. Natural bauxite makes a fairly good lining material, but its scarcity precludes its general use.

SECTION IV.

NEUTRAL REFRACTORIES.

The Ideal Furnace Lining is a neutral material, a substance that will permit of changing from acid to basic, or basic to acid, processes on the same lining. Two such substances are well known, but unfortunately the conditions of natural deposits will not permit of their use except in restricted quantities. These, are graphite and chromite.

Graphite: This substance is a natural product, though it can be prepared artificially in small quantities. It occurs mixed with calcareous or silicious rocks in Ceylon, Siberia, Austria, England, Brazil and New York. It requires expensive purification. It is infusible even at the temperature of the electric arc, but burns rapidly at that temperature, forming CO or CO_2. At the temperature of the open hearth it would be very slowly consumed. It is used in making special brick, crucibles, etc. Clay may be used as a binding material.

Chromite most nearly approaches the ideal refractory. Experience proves it to give equally satisfactory results in either an acid or a basic process. Its fusion point, about 2180°C., is far above the highest working temperature of the open hearth or blast furnace. It is difficult to set or sinter. In a finely ground condition and mixed with the proper proportion of slag, also finely ground, it is used regularly in the open hearth to daub ports and jambs and patch walls near the slag line. In the form of brick it may be used as dividing courses to separate acid from basic bricks, and in the bottoms of soaking pits, because it is impervious to pit cinder. The binding material for chromite brick is lime, or clay and lime.

Protection for Refractories: The fusion temperature of the materials discussed is amply high to withstand the temperatures of carbon heated

furnaces, if resistance to heat were the only requirement. But the refractory must possess strength, resistance to abrasion and corrosion, etc., and as these properties decrease rapidly with increase of temperature, it is desirable, in some cases necessary, to protect them as much as possible from the heat. This end is accomplished by backing the brick work with hollow metal forms through which water is kept constantly flowing. These forms are made of cast iron, steel, copper, or bronze, depending upon their use and position in the furnace, and may be in the shape of coiled pipes, hollow boxes, or sprayed jackets. As this course progresses, these devices will be frequently met with and their value demonstrated.

For purposes of comparison typical analyses of the various refractories will be found in the following table:

Table 3. Chemical Analyses of Refractories.

NAME	PERCENT OF												
	Silica	Iron Oxides		Alumina	Lime	Magnesia	Soda	Potash	Water	Titania	Chromic Oxide	Manganese Oxide	Carbon
	SiO_2	Fe_2O_3	FeO	Al_2O_3	CaO	MgO	Na_2O	K_2O	H_2O	TiO_2	Cr_2O_3	MnO	C
Ganister	98.20	.30	.....	.90	.15	.10	.....	.....	.....	.....	.....	..	.....
Low Grade Silica Sand..	91.60	3.48	.....	3.68	.10	.05	Trace	Trace	.....	.....	.....	.	.....
High Grade Silica Sand..	99.25	.31	.....	.20	Trace	Trace	.....	.....	.....	.....	.....		.....
Silica Brick...	96.42	.50	.....	.75	2.01	.08	.....	.....	.....	.06	.....	.	.....
Low Grade Fire Clay....	60.50	2.35	.40	24.95	.25	.05	.15	.....	10.00	1.40	.....	. .	.....
High Grade Fire Clay....	50.35	.75	.....	33.65	.10	.05	.10	.40	13.75	.80	.....	....	.....
Low Grade Fire Clay Brick..	61.72	6.43	.....	28.70	.46	1.04	.05	.05	.....	1.60	.....	.. ..	.....
High Grade Fire Clay Brick...	53.52	2.00	.....	41.00	.30	.30	.90	.20	.....	1.60	.....	....	.....
Calcined Magnesite...	3.96	5.81	.....	1.95	.40	87.45	.....	.....	.....	.....	.....	.. .	.....
Calcined Dolomite....	1.66	.94	.....	1.24	55.01	38.26	.....	.....	.....	.....	.....	.. .	.....
Bauxite.....	4.10	3.20	.....	60.80	.04	.04	.10	.....	30.08	1.62	.....	. ...	.....
Bauxite Brick..	8.82	6.30	.....	78.01	.98	4.41	.....	.....	.....	1.16	.....	.....	.....
Chromite.....	9.36	.....	13.50	10.60	Trace	21.06	.....	.....	.....	.....	43.97	.80	.....
Artificial (Coke—tar) Graphite....	5.95	.....	2.15	3.04	.43	.20	.....	.....	.....	.....	.....	.....	88.20
Natural Graphite Brick.....	13.04	....	.44	6.12	.....	.....	.....	.43	1.95	....	....	.....	77.80

SECTION V.

TESTING REFRACTORIES.

Trial Tests and Laboratory Tests: The best test for a refractory is a trial test in which the material is placed in actual service under the most trying conditions it will be expected to stand up under. As such tests can seldom be made on material for new work and as there may be considerable variation in raw materials and in methods of manufacture, laboratory tests are necessary. Such tests are not always conclusive, owing to the difficulty of obtaining laboratory conditions identical to those in actual practice. They are, however, very useful for the purpose of comparisons, and, if the conditions of the tests are sufficiently severe, the more serious defects will be revealed. These tests are chemical and physical. From the chemical analysis the composition of the material is determined and its quality is judged. As the method of manufacture and the care with which it is carried out affect the properties of the refractory, the chemical test should be, and usually is, supplemented by physical tests. Chief among these tests are the fusion or softening point, crushing strength, expansion and contraction, slagging, porosity, density, resistance to compression, impact, abrasion and spalling tests. Each of these tests may be made in a comparatively simple manner, but care and judgment are required to see that the conditions of the tests conform closely with those to which the brick are to be subjected in actual service. On this account some of the tests usually employed will not be applicable to the iron and steel industry, while others must be modified to conform to its conditions. The tests here described are those particularly suited to this industry.[1]

The Fusion Temperature, in ordinary practice, is usually determined by means of Seger cones. These are small triangular pyramids, 6 cm. high, with a base of 2 cm. They are composed of aluminum silicates. Cone number 28 contains ten parts silica to one part alumina and corresponds to a temperature of 1630° C. The fusion temperatures of succeeding cones up to number 40, which corresponds to a temperature of 1920° C, are increased by decreasing the proportion of silica to alumina. For lower temperatures varying amounts of alkali or lime are added. By this means the melting point is so controlled that a series of cones may be prepared with melting points between the limits of 500° C and 1900° C. Upon being gradually heated to a sufficiently high temperature, these cones will soften and slowly bend until their tops touch the floor, which point is taken as their fusion point. In making a test, a pyramid of the material to be tested, having the same shape and dimensions as the standards, is placed in a furnace with two or more standards having melting points estimated to be near that of the material to be tested. As the temperature of the furnace is raised, the standard cone that melts at the same time as the test will register the temperature of the fur-

[1] See Practical Methods for Testing Refractory Fire Brick by C. E. Nesbitt and M. L. Bell. Proceedings of the American Society for Testing Materials. Vol. XVII, 1916.

nace and the fusion point of the test. The softening temperature is considered to be that at which the specimen bends, sags or puffs out of shape. Instead of the standard cone, the more accurate pyrometer is coming into use for making this test.

Resistance to Compression: The ability of brick to withstand pressure at a high temperature is a very important property. This test is made on a modified form of Brinell ball testing machine. The ball is made of steel and is 2½ inches in diameter. In making this test, the brick is uniformly and slowly heated from atmospheric temperature to 1350° C and held in the furnace at this temperature for three hours or longer, when it is removed and placed flat under the ball of the machine, and a pressure of 850 lbs. is immediately applied, which is gradually and uniformly increased at such a rate that a maximum load of 1600 lbs. is attained at the end of five minutes. The depth of the depression made by the ball is taken as the measurement of the resistance of the brick to compression.

Expansion and Contraction: A brick must be prepared for this test by grinding the ends so that they will be parallel to each other and at right angles to the sides. Its length is then measured by means of a specially constructed micrometer. The brick is next heated to the temperature at which it is to be used, removed from the furnace and immediately measured. The expansion or contraction is expressed in inches per lineal foot.

Slagging Test: By this test the impermeability of the brick to molten slag is determined. The brick is prepared by drilling two circular cavities, 2½ inches in diameter, each at the intersection of the diagonals of the rectangles formed by bisecting transversely the unbranded face of the brick, to such a depth that the area of the greatest cross section is 1.7 inches. The brick is then heated as in the compression test. When the temperature has reached 1350° C, 35 grams of a standard blast furnace slag is placed in one cavity and 35 grams of a standard heating furnace slag in the other. Both slags are pulverized to pass a 40 mesh sieve. The temperature of 1350° C is maintained for two hours after the slag is added, at the end of which time the brick is removed from the furnace and, when cold, sawed lengthwise so as to bisect both cavities, thus exposing the part of the brick subject to slag penetration. The area penetrated by the slag is measured with a planimeter and expressed in square inches.

Density: The density is determined from the weight of the brick in air and its dimensions. This method gives the apparent specific gravity. This test is greatly influenced by the method of manufacture, being affected by both the amount of water used in pugging and the pressure in moulding. While in manufacturing practice the amount of water added is determined by the plasticity of the clay, investigations have shown that the moisture content should be about 8 per cent. and the pressure about 1500 lbs. per square inch to secure the greatest density.

The Impact Test: This test is important in the case of brick to be used in blast furnace tops, where they are subject to much impact from lumps of ore, stone, and coke in charging. The test is greatly affected by temperature. A brick heated to 260°C. was found to be 20 per cent. weaker than one of the same brand tested at 20°C., and 40 per cent. weaker when tested at 540°C. In carrying out the test, the brick is first heated from atmospheric temperature to 260°C., the temperature being raised gradually through a period of one hour. The brick is then placed end up in a machine, by means of which a steel ball 2½ inches in diameter and weighing 2.34 lbs. is dropped upon the longest axis of the brick from heights successively increasing by two inches until the brick breaks. The height in inches of the ball in the last test is taken as the measure of the resistance of the brick to impact.

The Abrasion Test: This test aims to determine the wearing qualities of the brick at the temperature to which it is subjected in actual service. The brick is heated to the required temperature, and its end then pressed against a carborundum wheel for a given time and with a fixed pressure. The brick must be ground to uniform thickness and a preliminary cut made, so the wheel will cut through the entire thickness from the beginning of the test. The depth of the cut made on the hot brick measures the abrasion. It is obvious that the test will be affected by the width of the cutting wheel, the speed at which it revolves, also the grade and grit of the carborundum, all of which must be fixed and constant.

Spalling Test: Spalling in a brick is usually produced by temperature changes, often accelerated by mechanical pressure. The drawbacks with this test are the fact that it must be made much more severe than the conditions of actual service and that it concerns the brick only as made, thus neglecting the effect of slag penetration and the resulting vitrification that often causes brick to spall in service. The test is usually made on several bricks. The bricks are dried at 100° C. for 5 hours or more, weighed, and then placed in the door of a furnace, heated to 1350° C., so that one end only is exposed to the interior heat of the furnace. The remainder of the door space, if any, is then filled with other brick. After heating for one hour at this temperature the bricks are removed, and each one is immediately plunged into two gallons of water at 20° C. to a depth of four inches and held there for three minutes. It is then withdrawn from the water, allowed to dry three minutes, and returned to the furnace as before. This operation is repeated until the bricks have been plunged ten times, when they are dried at 100° C. for five hours or more and again weighed. The percentage of loss in weight, which is taken as a measure of the spalling, is calculated from the original weight.

CHAPTER III.

IRON ORES.

SECTION I.

ORES AND THE IRON BEARING MINERALS.

Minerals and Ores: Any homogeneous inorganic substance that occurs naturally in the solid state is called a mineral. A mineral, therefore, may be either an element or a compound. While a few elements, like gold and platinum, occur for the most part native, and others, like silver, copper, mercury, sulphur and carbon, may be found both native and combined, most minerals, of which some 800 varieties have been discovered and named, such as quartz, feldspar, hematite, hornblende, calcite, mica, etc., or their species, represent definite chemical compounds. Owing to the many forces that are constantly at work in nature and the wide distribution of some of the minerals, it is seldom a deposit consisting of but a single mineral is encountered. It is of such natural deposits that the ores are constituted. In general, then, an ore is defined as a mineral or a mixture of minerals from which one or more elements may be extracted with profit.

The Iron Bearing Minerals: While there is a vast number of mineral species that contain iron, there are only a few that are of any importance commercially, because, in most cases, either the iron content is too low to justify the extraction of the metal or the mineral itself does not occur in sufficient abundance to make it available for use as an ore. Grouped according to their chemical composition, the iron bearing minerals of chief importance are divided into four classes; namely, the iron oxides, iron carbonates, iron silicates, and iron sulphides. Of these, only the first class may be considered as a factor in the manufacture of steel in the United States. These oxides go to form a large number of minerals, which have been grouped and named as shown in the following table:

Table 4. Chief Iron Bearing Minerals.

Chemical Name	Mineralogical Name.
1. Ferroso-ferric Oxide	Magnetite
2. Anhydrous Ferric Oxide	Hematite
3. Hydrous Ferric Oxides	Limonite and others
4. Ferrous Carbonate	Siderite
5. Iron Silicates	Chloropal and others
6. Iron Sulphides	Pyrite and others

Magnetite Group: The only important mineral of this group is magnetite, chemical formula Fe_3O_4, composed of iron, 72.4 per cent., and oxygen, 27.6 per cent. The mineral is found in Arkansas, Pennsylvania, New Jersey, and New York. It varies in color from gray to black, has a specific gravity of about 5.0, and is magnetic. This last named property is taken advantage of in locating ore bodies below the surface of the ground and in mechanically purifying ores of this group by magnetic concentration. It is often found closely associated with igneous rocks, when it is apt to contain appreciable amounts of chromium or titanium oxides which cannot be removed from it by magnetic concentration. The remaining magnetic ores of the United States are, for the most part, of a low grade and require dressing, but the magnetite ores of Sweden represent the purest ores in the world and are of a grade approaching that of the pure mineral. However, only about 5 per cent. of the world's supply of iron is obtained from magnetite.

Hematite Group: The typical mineral of this group is hematite, which contains the equivalent of 70 per cent. metallic iron, based on the chemical formula Fe_2O_3. It furnishes the base of the world's most important ores. Being associated with rocks of various geological periods, these ores occur widely distributed, and in a variety of forms, which differ greatly in their iron content. Many of these varieties are known, from their outstanding characteristic, as red hematite, specular hematite, oölitic hematite, fossil ore, etc.

Limonite or Brown Ore Group: The minerals of this group are all hydrous ferric oxides, and may be represented, as a group, by the general formula $m\,Fe_2O_3 \cdot n\,H_2O$. There are five of these minerals, and they have been named, in the order of their progressive increase in water content, turgite, $2Fe_2O_3 \cdot H_2O$; goethite, $Fe_2O_3 \cdot H_2O$; limonite, $2Fe_2O_3 \cdot 3H_2O$; xanthosiderite, $Fe_2O_3 \cdot 2H_2O$; and limnite, $Fe_2O_3 \cdot 3H_2O$. On a theoretical basis the iron content of this series will vary from 52.31 per cent. to 66.31 per cent. These minerals are widely distributed throughout the United States. In southern Virginia they make up the greater part of the available ores, all of which are low in iron content and high in silica. In the early history of the United States, these ores were important sources of iron, but under present conditions they can be utilized only to a limited extent.

The Carbonate Group: The representative member of this group is the mineral known as siderite, or iron carbonate, $FeCO_3$, which contains 43.8 per cent. of iron. Owing to the fact that carbonic acid is dibasic, a part of the iron required to neutralize it may be replaced by other metals, thus giving rise to a series of minerals, such as iron-calcium carbonate, iron-magnesium carbonate, etc. Some of the names commonly applied to these ores are spathic iron ore, kidney ore, blackband ore, etc. The ore deposits in which this group appears are of little commercial importance in the United States, for they make up only about ½ per cent. of the known ore resources. In England they make up the ores of the Cleveland district,

which produces about 70 per cent. of the domestic ore supply of that country. Usually, carbonate ores are calcined before they are charged into the blast furnace.

The Mineralogical Make-up of Iron Ores: As was indicated at the beginning, an ore deposit at best represents but a mixture of different minerals, only a part of which will contain the element or elements sought. All iron ores, then, may be looked upon as being made up of these two parts: One part is composed of the iron bearing minerals, which represent definite compounds of iron; the other part includes all the other substances mixed with these compounds, and is known as the gangue of the ore. Evidently, the richness of the ore, by which term is meant the proportion by weight of iron to all other elements in the ore, depends on the composition of the iron bearing minerals it contains and upon the amount of gangue associated with them. In working up the ores, their physical condition must also be taken into consideration. In this respect, they are subject to the widest variation, ranging from soft clay-like or earthy matter to hard compact masses. Both extremes tend to give trouble in the blast furnace. Thus, the soft fine ores are so apt to choke up a furnace, not designed to use them, that they were once considered practically worthless. The successful smelting of these ores represents one of the great achievements of American furnacemen. One objection to very fine ores, and one that has not yet been overcome, is that they give rise to large amounts of flue dust, which interferes seriously with the economical utilization of the furnace gases. On the other hand, the very hard and dense ores, which enter the furnace in the form of comparatively large lumps, are difficult to reduce and require an excessive amount of fuel.

SECTION II.

VALUATION OF ORES.

Factors in the Valuation of Ores: Omitting relative property valuations, prices of competitive ores, costs of transportation, and other considerations of a purely business nature, the chief factors that determine the value of an ore are its richness, its chemical composition and its accessibility. The richness of the ore will, of course, be made the basis for the valuation. For this purpose a unit system is employed, a unit of iron corresponding to one per cent. But the prices of ores do not rise and fall parallel with the number of units of iron they contain, because the gangue to be disposed of must also be considered. For example, suppose two hematite ores containing 63 per cent. and 42 per cent. iron are being considered. In the first, 90 per cent. of the ore is pure mineral, leaving only 10 per cent. as gangue to be disposed of, but the second represents only 60 per cent. pure mineral with 40 per cent. of its weight as gangue to be fluxed and transported. Next to richness comes the consideration of the chemical composition of the ore as a whole, for certain impurities, when present in only relatively small amounts, may make a rich ore worthless. Without taking the time to consider all the possibilities in this connection, the more common impurities in ore may be classed as follows:

1. **Those impurities that are never reduced in the blast furnace** and so do not affect the composition of the iron are alumina, Al_2O_3; lime, CaO; magnesia, MgO; and the alkalies, soda, (Na_2O), and potassia, (K_2O). All these substances, it will be observed, are strong bases, with the exception of alumina which may be either an acid or a base. Therefore, the presence of these substances in the ore may not be objectionable, for the lime and the magnesia, in particular, are valuable as fluxes. Alumina, also, up to about 5 per cent., may play a useful part in regulating the blast furnace. The alkalies for the most part are driven off with the flue dust, and with modern appliances they may be recovered, when present in sufficient amount to justify the installation of the necessary apparatus, so that they may form a valuable by-product.

2. **Those impurities that may be partially reduced** in the furnace and give elements that enter the pig iron are silica, or the silicates, sulphates and manganese compounds. Of these, the silica, which term includes both the free silica and the silicates, constitutes a large part of the gangue of most ores, and as it requires an equal weight of lime or magnesia to flux it, it must be considered in fixing the value of an ore. Owing to the fact that the amount reduced in the blast furnace is subject to control to a considerable extent and that the element is readily removed during the process of purifying the pig iron, it is not considered of much importance from the standpoint of its effect on the steel produced from the iron. This attitude toward silica is just the opposite of that displayed toward the sulphur compounds. All these compounds are reduced in the furnace to sulphides, in which form the sulphur enters either the metal as ferrous or manganese sulphides or the slag as calcium sulphide. Now, there is a limit to the quantity of sulphur a given slag can absorb, the highest figures given being less than 5 per cent., and, naturally enough, the nearer this limit is approached, the more difficult it becomes to keep the sulphur out of the metal. Since even comparatively small amounts of this element exert an evil influence in steel, and it can be removed from the metal only partially and with much difficulty, the importance of this element in fixing the value of an ore is evident. As to the manganese compounds, the amount of this element that enters the iron varies with the manganese content of the ore and takes place to the extent of nearly 75 per cent. of the manganese charged. The per cent. of this element is, therefore, considered in its relation to the iron content. An ore is available for the manufacture of the ordinary grades of pig iron when the manganese content does not exceed 2 per cent. of the iron content; between 2 per cent. and 10 per cent., calculated on the same basis, it is necessary to mix the ore with others containing little of this element; but if the manganese content is 15 per cent. to 20 per cent. of the iron content, then the ore becomes available for the manufacture of spiegel.

3. **The impurities always reduced** in the furnace are all the compounds of phosphorus, which element enters the pig iron only. While this element is easily removed from the metal by basic processes, none at all is eliminated by the acid processes, with the result that acid steels contain a higher percentage of this element than the average of the charge from which the steel is produced. This element, therefore, is the basis for the separation of all ores into the two great classes, known as **Bessemer** and **basic**. This division, like that for manganese, is made on the basis of the relation of the phosphorus content to iron content of the ore. Since it is desirable to produce Bessemer steel that will contain not more than .100 per cent. of its weight as phosphorus, a true Bessemer ore would be one whose phosphorus content plus the phosphorus content of the coke and limestone required to smelt and flux it would produce a pig iron with a phosphorus content not exceeding .090 per cent. Allowing 10 per cent. for conversion loss, such a pig iron would give a steel containing less than .100 per cent. of its weight of phosphorus. Commercially, however, since commercial tolerances usually permit the phosphorus in the steel to rise as high as .110 per cent., no allowance is made for conversion, and a commercial Bessemer ore is one whose phosphorus content plus some arbitrary figure, usually about .015 per cent., to allow for the phosphorus acquired from the flux and fuel, is less than one one-thousandth of its iron content. Thus, the per cent. of phosphorus in an ore containing 60 units of iron must be .045, or less, to be classed as a Bessemer ore, for 1/1000 of 60=.060 and .060—.015=.045. Another method for determining the grade of an ore is explained by the following example:

Question: To what class does an ore containing 60 per cent. iron and .045 per cent. phosphorus belong?

Solution:

.045÷.60=.075=per cent. phosphorus in the pig iron, acquired from the ore.
.020=Estimated per cent. phos. in pig iron, acquired from coke and stone.

Ans. .095=per cent. phosphorus in the pig iron. Therefore, the ore is of Bessemer grade.

Water or moisture is another factor to be considered in the valuation of ores, because it adds to the weight of ore to be handled and transported. The importance of this matter in fixing the value of an ore is seen at once when it is pointed out that many of the soft ores of the Lake Superior region carry as much as 12 per cent. of their weight as hygroscopic water, and a few as much as, or more than, 15 per cent. This moisture content for any particular ore is much more nearly constant under varying weather conditions than might be expected; but in the case of different ores there is a wide variation, ranging from .40 per cent. in some of the hard red hema-

tites to 16.80 per cent. in a few of the soft red ores. These points are well illustrated by the table below, the examples of which have been selected because they show about the same iron content when dry.

TABLE 5. Analyses of Ores Illustrating Dry and Wet Basis.

ORE	STATE	% Iron, Fe	% Phos, P.	% Silica SiO_2	% Mang. Mn.	% Alumina, Al_2O_3	% Lime, CaO	% Magnesia, MgO	% Sul. S.	% Ignition Loss	% Moisture, H_2O
A. (Marquette Range)	Dry	57.36	.137	15.62	.08	1.26	.68	.33	.007	.03	.....
	Natural	56.82	.135	15.47	.08	1.25	.67	.327	.007	.03	.944
B. (Missabe Range)	Dry	57.03	.042	12.48	.56	1.69	.21	.32	.010	2.80	.....
	Natural	52.54	.039	11.50	.52	1.56	.19	.29	.009	2.58	7.87
C. (Missabe Range)	Dry	57.06	.081	7.33	1.72	1.00	.30	.40	.010	2.00	.....
	Natural	47.47	.067	6.09	1.43	.83	.25	.32	.008	1.66	16.80

The marketing of the ores and all the metallurgical calculations involving them are based on the analyses of samples dried at 100°C. It will be observed that drying at this temperature may not drive off water of crystallization and that in the case of the brown hematites a much higher temperature than the drying temperature is required to drive off all the combined water.

Accessibility: It is evident that the economic importance of an ore deposit depends to a great extent upon its size and its location, both geologic and geographic. Thus, an ore that is very desirable from the standpoint of chemical composition and physical condition, may be so located as to be practically inaccessible; or granting it can be made accessible, the amount of ore in the deposit may not justify the expense of opening it up. On the other hand, a poor ore may be so conveniently located that it may be concentrated at a profit. A thorough discussion of this topic cannot be undertaken in the brief space allotted to this chapter. Suffice it to say, that the working of any ore body under modern conditions presents difficult engineering problems both in mining and in transportation. Perhaps the best way to impart some understanding of these problems is through a brief description of the ore mining operations of the Steel Corporation, itself. With the exception of the Tennessee Coal, Iron & Railroad Company, which obtains its ore from the Birmingham District in Alabama, all the constituent companies of the Corporation depend upon the Lake Superior district for their ore supply.

SECTION III.

THE BIRMINGHAM DISTRICT.

Location and General Geology: The Birmingham District includes the area from which the furnaces at Birmingham, Ensley, and Bessemer secure their iron ores, and is co-extensive with Birmingham Valley. This Valley extends from the City of Birmingham in both a northeast and southwest direction for a total length of about 75 miles and a width of about six miles. The ore, which is a variety of red hematite, occurs in the Clinton formation, which consists of shale, sandstone, iron ore, and a little ferruginous limestone. Geological researches conducted by the government[1] indicate that the ore was formed at the same time as the rocks with which it is associated. The valley lies within the area originally covered by this formation, which, therefore, occurs on both sides and dips away from it on each. But it is only in Red Mountain that the ore bed has been found of sufficient thickness and purity to justify its being worked on a large scale, and nearly all of the most productive mines are located in a section, about 62 miles long, of this mountain between Narrow Gap and Sparks Gap.

Method of Mining: All of the red ore mines in the Birmingham district were started as open cuts along the outcrop, and the product of these surface mines, having been leached, were at first soft ore. At a few points these simple mining operations are still carried on, but, owing to the dip of the ore beds, all mines from which any large quantity of ore has been taken are now completely underground and are operated by means of slopes or inclines. At these greater depths the ore is very hard and compact. On account of the fact that the southern portion of the ridge is overlaid by more recent formations, the ore gradually becomes more and more deeply buried on passing southward, and all the deepest slopes are in the strip of mountains south-west of Birmingham. The deepest slope at this southern extremity of the district extends downward on beds whose average dip is about 22°. The co-existence of the ore with limestone and the proximity of coal beds suitable for making coke give this district an advantage over other districts of the country. The ore contains phosphorus to the extent of about .8 per cent., which is much higher than other basic ores of the country. By employing the duplex or the triplex processes in refining the pig iron, a slag with a high phosphorus content is produced that is available as fertilizer for agricultural use.

SECTION IV.

THE LAKE SUPERIOR DISTRICT.

Importance, Location and General Geology: During recent years the Lake Superior district has provided approximately four-fifths of the entire iron ore output of the United States, and there is nothing to indicate but that the region will, for many years to come, continue to be the nation's

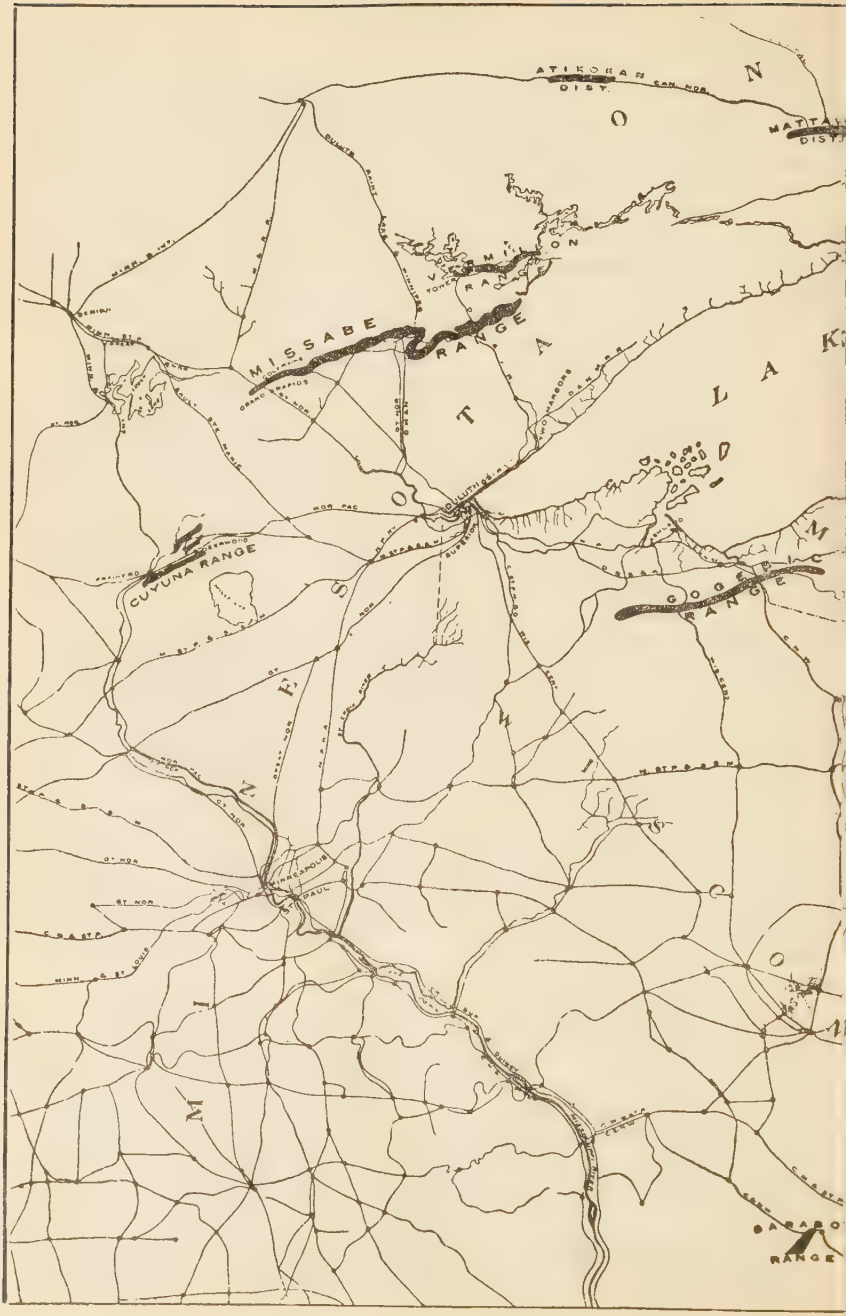
[1] See Bulletin U. S. Geol. Survey No. 315, 1907. The Clinton or Red Ores of the Birmingham District, Alabama, by E. F. Burchard, also Bulletin U. S. Geol. Survey No. 340. Investigations relating to Iron and Manganese, by E. F. Burchard, A. C. Spencer, W. C. Phalen.

most important source of ore supply. This district, which surrounds Lake Superior, contains certain isolated areas, or ranges, where bodies of iron ore have been discovered. These ranges are scattered over the northern part of the states of Michigan, Wisconsin and Minnesota and also a part of the Canadian province of Ontario. Investigation has proven that these ore bodies occur at certain well defined geological horizons and are associated with certain rocks. Geologically, the Lake Superior deposits are much older than the Clinton ores of the Birmingham district, being associated with rocks of pre-Cambrian age. According to the conclusions of those who have made a study of the area, the iron was originally deposited as an integral part of certain sedimentary rocks. Following their deposition and solidification, these rocks were elevated and folded, after which surface waters, bearing different compounds in solution, percolated through them, and, through chemical action and solution, concentrated the iron in the troughs which had been formed by the folding of the formation or by the intrusive dikes which had cut across the strata. Much later, with the retreat of the ice at the end of the glacial epoch, these ore bodies were left covered by varying depths of glacial drift. In the order in which they were opened the six chief areas, or ranges, lying within the borders of the United States, are Marquette, Menominee, Gogebic, Vermilion, Missabe, and Cuyuna.

The Marquette Range lies near the southern shore of the lake in the state of Michigan, and a short distance west by south of the lake city of Marquette, from which it takes its name. Besides Marquette, the towns of Ishpeming, Negaunee, Champion, Republic and Gwinn are also included within the area. The formation is narrow as compared with its length and very irregular, but its general direction is from east to west. The original outcrop was very conspicuous and was responsible for the early discovery, in 1844, of the deposit, which, as indicated above, was the first of the great ranges to be worked. It was opened in 1854, and up to 1923 about 140,353,500 long tons of ore had been taken out of it. The largest yearly shipments were 5,396,007 tons in 1916. The ore is partly hematite of the red, soft variety, but there are smaller amounts of magnetite and limonite and some hard hematite.

The Menominee Range is also in the state of Michigan. It lies several miles due south of the Marquette range and is, hence, nearer Lake Michigan than Lake Superior. It includes the towns of Iron Mountain, Vulcan, Norway, Florence, Alpha, Crystal Falls and Iron River. The principal belt, composed mainly of hematite, extends in a direction from east to west. Only a part of the range is productive, but up to 1923 more than 132,712,800 long tons of ore had been mined from it. The largest annual shipments, 6,569,384 tons, were made in 1920. It was opened in 1872.

The Gogebic Range lies almost due west of the Marquette range, and, extending as a narrow belt in a direction from a point a little north of east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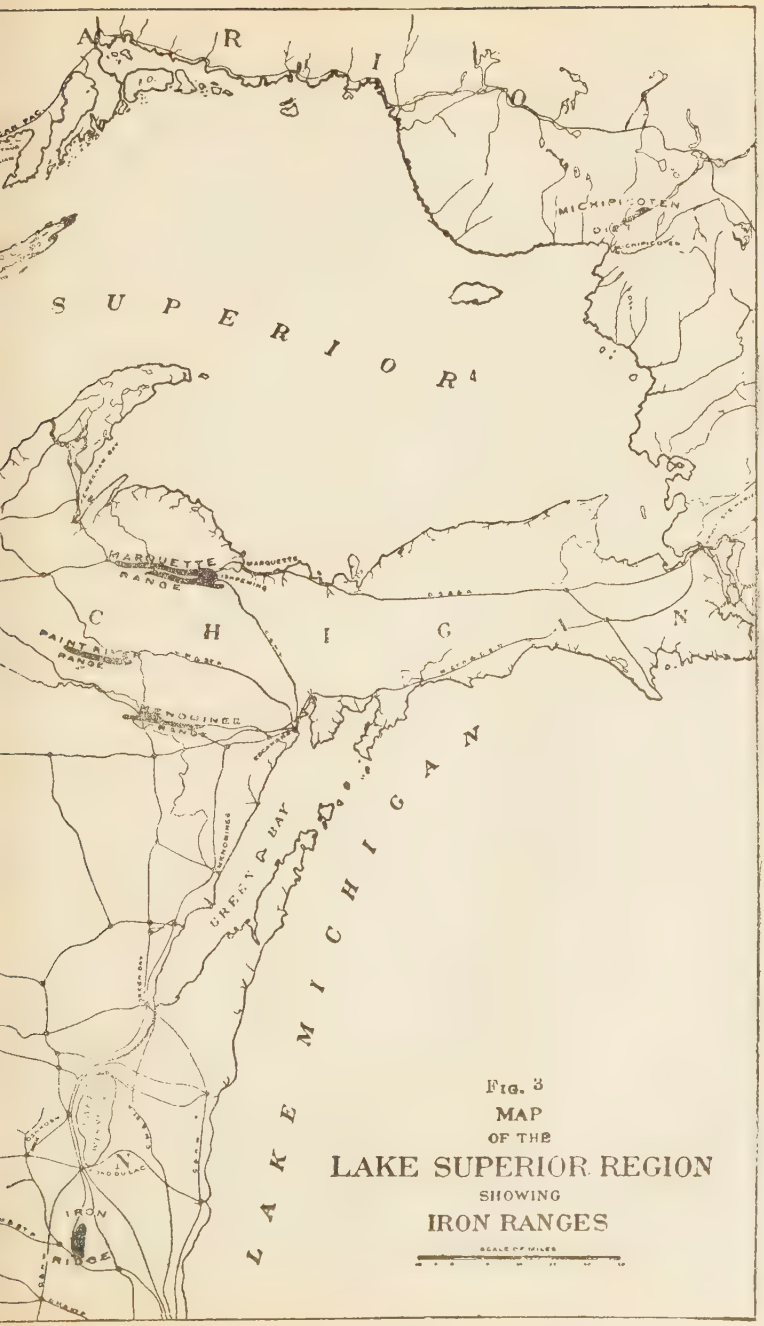


FIG. 3

MAP

OF THE

LAKE SUPERIOR REGION

SHOWING

IRON RANGES

SCALE OF MILES

to a point a little south of west of its center, it is located partly in Michigan and partly in Wisconsin. The area includes the towns of Hurley, Ironwood and Bessemer. The original iron formation, which dips sharply toward the north, rests on quartzite, and is cut by igneous dikes that extend at almost right angles to the original quartzite. The dike and the impervious strata thus combine to form troughs, in which ore bodies have been formed by concentration. The ores, which are mostly soft and red, represent partially dehydrated hematites, with subordinate amounts of hard, blue hematite. The range was opened in 1884, and in 1923 there had been produced from it more than 134,358,400 long tons of ore. The largest yearly shipments were for 1920,—8,763,332 tons.

The Vermilion Range was opened the same year as the Gogebic range. It lies in northeastern Minnesota, and includes the towns of Tower, Soudan, and Ely. The whole district is one of complex folding, so the ore deposits occur in narrow belts, which are enclosed on the bottom and sides by original greenstones of Archean age and on top by the original iron formation. As the pitch or slope is very steep, the outcrops are very small. The ores are all hard and are composed of red and blue hematite. This range had contributed a little more than 46,267,725 long tons of ore by 1923. The largest shipments for one year were 1,947,200 in 1916. This range and the three previously mentioned are known as the old ranges to distinguish them from the more recently discovered Missabe and Cuyuna ranges.

The Missabe Range is one to excite the interest of every one interested in the manufacture of iron or steel, because from it comes the greater part of the ore used for the production of pig iron today. It was opened in 1892 and up to 1923 about 602,207,000 long tons of ore had been taken from its mines. The largest shipments for one year were 42,526,612 tons in 1916. It lies in Minnesota, northwest of Lake Superior, and extends in an east and west direction approximately 100 miles. The principal towns are Biwabik, Eveleth, Virginia, Chisholm, Hibbing, Nashwauk, and Coleraine. The iron formation is the Biwabik in the Upper Huronian. It lies along the southern slope of a ridge that is known as the Giants, or Missabe, Range, and has a gentle slope toward the south. The surface is covered with glacial drift, and rock exposures are not common. This surface, originally covered with forest, gave few signs to indicate the presence of ore bodies. The slope of the iron formation is gentle, so most of the ore deposits are flat-lying and have a large horizontal area compared with the deposits on the other ranges. The impervious basement under the ore deposits is formed by layers of slate or paint rock, interbedded with the iron formation. The ores are mostly soft and hydrated hematites and limonite. They vary in texture from very fine dust to fairly coarse, hard and granular ore. Toward the western end of the district, layers of sand are often interbedded with the ore, forming the so-called "sandy" ores, which require concentration to form ore of commercial grade. The deposits are all comparatively shallow.

The Cuyuna Range, which is the last range of any importance to be discovered, was opened in 1911. It is located in Crow Wing County, Minnesota, about 100 miles west of Duluth. The principal towns in the district are Deerwood, Crosby, and Brainerd. The range has no marked topographic features, the surface being level and covered with a heavy mantle of sand. Since there are no surface indications to assist in the exploration for ore, the presence of lines of magnetic variation must be depended upon almost entirely. By drilling, these lines have been found to be associated with belts of iron-bearing formations which trend in a northeasterly and southwesterly direction. The formation is interfoliated with slate and schist, and is usually steeply tilted. At some localities igneous intrusive rocks occur. The ore deposits are usually lenticular in form. In certain restricted areas of the range, particularly in the northern part, manganiferous iron ores have been found. The deposits of these ores occur in irregular pockets or lenses, and contain as high as 45 per cent. manganese. Some of these bodies of ore are being worked for their manganese content only. In 1918 the yearly production reached 2,478,923 tons, and the total production at the beginning of 1923 had reached 15,836,900 tons.

SECTION V.
MINING THE LAKE ORES.[1]

Prospecting and Exploration: Since the Lake Superior ores occur in pockets or distinct bodies and vary much as to character and location, the actual mining of the ores is preceded by much work of an exploratory character. This work includes **prospecting** and **exploration.**

Prospecting is the term generally applied to the quest for surface indications of ore, or the conditions which would warrant the expectation of finding ore in the vicinity. It includes such quest operations as geological examination, dip needle work, shallow test-pitting, and trenching. The ore bodies of the Missabe Range are non-magnetic, and dip needle prospecting is therefore valueless. On the Cuyuna Range, however, magnetic attraction as evidenced by the dip needle has been extensively employed as a guide to the location of ore deposits; in other localities it has also found limited application.

Drill Exploration: After the presence of an ore deposit is known or suspected, resort is generally had to exploration by means of diamond or churn drills. On the old ranges geological conditions generally make this manner of ascertaining the exact limits of an ore deposit impracticable; so, if two or three adjacent drill holes develop considerable depths of ore, the sinking of a shaft for underground exploration, development and mining is generally considered warranted. On the Missabe Range, however, the flat-lying and comparatively shallow characteristics of the ore formation warrant much more extensive drill explorations. On this range, then, an ore body is almost invariably followed out with the drills, and its limits

[1]For further details concerning the mining of the Lake Ores, see Minn. School of Mines Experiment Station Bulletin No. 1, Iron Mining in Minnesota, by Charles E. Von Barneveld, University of Minnesota, Minneapolis, Minn.

FIG. 4. Open Pit Mining.

are determined to the point where the complete plan of development can be worked out in advance of actual mining operations.

Methods of Mining: Both open pit and underground methods of mining are employed in the mines of the Lake Superior District. On the old ranges, where the ore bodies often extend to great depths and usually lie at angles so steeply inclined to the horizontal that the surface exposures, or outcrops, are small, underground mining methods are employed almost without exception. On the Missabe Range the ore bodies are, as a rule, flatlying with relatively large areas of outcrop, and open pit mining is, therefore, general. Of course, there are many deposits on this range that, on account of limited operating area, excessive depth of over-burden, or for other reasons, must be mined by underground methods, and there are, therefore, a large number of underground mines also. But by far the greater part of the tonnage produced from the Missabe Range comes from open pits.

Open Pit Mining: Before deciding whether an ore body should be mined by underground methods or as an open pit, a detailed operating-analysis is made of the proposition to determine by which method the ore can be mined most economically. Estimates are made determining the yardage of overburden, or "stripping", that must be removed to uncover the ore body, the tonnage of ore which can then be mined by steamshovel, and the additional tonnage which can be "scrammed" or "milled" in the pit after the limits of steamshovel operation have been reached. Then the cost of the entire operation, including interest-charges on the necessarily large investment in stripping removal, is calculated and reduced to a final cost per ton of ore recoverable. If this figure is less than the probable cost per ton of underground mining, and if the other operating conditions are satisfactory, open pit operation is, of course, deemed advisable. The laying out of an open pit mine involves the following engineering problems: first, outlining the area of ore which it will pay to strip, i. e., considering the two factors of depth of ore and thickness of overburden; second, planning the disposal of stripping which it will be necessary to remove to uncover the ore body, for this material must often be hauled considerable distances from the pits to dump grounds; third, locating the track systems outside the pit for the transportation of stripping and the hauling of ore; fourth, designing the system of railroad tracks within the pit that will make available the maximum quantity of ore accessible by steamshovel, which designing generally involves a series of switchbacks on limiting operative grades and curvature; fifth, providing for drainings of the pit; and sixth, planning in advance for the mining of the ore that cannot be mined by steam-shovel. The general term **open pit mining** covers three recognized methods of mining, i. e., steamshovel, milling and scramming. **Steam-shovel mining,** of course, needs no description; it is simply the loading of ore directly into railroad cars by steamshovel.

FIG. 5. Open Pit Mining. Showing 300-ton Steam Shovel in operation. The dipper of this Shovel holds 8 cubic yards or 15 tons of ore.

Milling is a term applied to a thoroughly well worked out system of open pit mining, extensively prosecuted in the early days and still applied under suitable conditions. It consists of the following operations: first, the removal of the overburden from the ore body to be mined, this being done by steamshovel; second, the sinking of a hoisting shaft or incline to the bottom of the ore and the development of a system of underground

FIG. 6. Milling Pit.

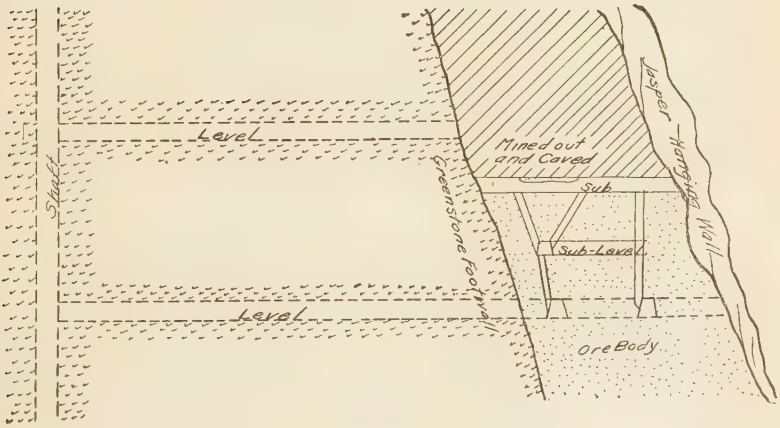
tramming drifts tributary to the shaft and underneath the ore to be mined; third, the putting up of a number of raises (vertical openings) extending from the underground drifts through the ore; fourth, "milling" or shoveling the ore into the raises, through which it is drawn into tram cars operating in haulage drifts that lead to the shaft or incline, where it is hoisted to the surface. The milling system of mining can well be applied to small ore bodies which can be successfully stripped, but where the resultant open pit areas are too small to permit of steamshovel operation; also, as a sequel to steamshovel mining in larger pits where considerable depths of ore remain after the limits of steamshovel work have been reached.

Scramming is a term applied colloquially on the Missabe Range to the operation of recovering shallow pockets and hummocks of ore left unmined in and around the open pits following the period of steamshovel mining. It is a general term inclusive of hand work, scraper work, mining with dragline excavators, etc., and is applicable generally to the operation of "cleaning up" a pit after its period of real production has passed.

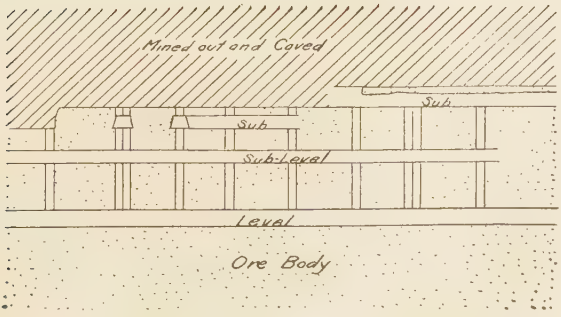
Advantages of Open Pit Mining: It is very apparent that open pit mining, when feasible, offers decided advantages as compared with underground methods. Probably, the most evident of these is the possibility of big production; in 1916 the Hull Rust Mine alone shipped 7,665,611 tons of ore,—more than 10 per cent. of the total mined in the United States during that year, which, according to the U. S. Geological Survey, amounted to 75,167,672 tons. Where the overburden is light in comparison with the depth of ore, and stripping charges are not heavy, open pit mining produces low cost ore. It accomplishes a great saving in labor; the output per man per day from the open pit mine is many times that from the average underground mine. Aside from the skilled operators of the steamshovels and locomotives, common labor only is required in open pit mining, while in underground work the miner is a rather high class workman, and he receives a relatively high wage. Owing to this latter condition, strikes have never been able to interfere seriously, so far, with the output of Missabe Range open pit mines.

Underground Mining—Slicing: The system of underground mining most generally in use in the mines of the Missabe Range, and in the soft-ore mines of the old ranges, as well, is known as **top-slicing and caving.** The development of a mine under this method is as follows: First, a shaft is sunk to the bottom of the ore body, or to such depth in the ore as has been determined as desirable. Second, after cutting a "station," pumproom and pocket at the bottom of the shaft, a main haulage drift, or system of haulage drifts, is driven out underneath the ore body. Third, raises are put up from the haulage drifts at intervals of about 50 feet along the drifts through the ore body to the top of the ore. Fourth, cross cuts are driven from the tops of the raises to the limits of the ore body or the property lines, the cross cuts being parallel and the same distance apart as the

raises. Fifth, beginning at the ends of the cross cuts farthest from the raises, the ore is "sliced" out between cross cuts, trammed to the raises, dumped into the latter, drawn off thru chutes into cars operating on the main haulage level, hauled to the shaft, dumped into the shaft pocket and hoisted to the surface, where it is either loaded direct into railroad ore



IDEAL CROSS SECTION



IDEAL LONGITUDINAL SECTION

FIG. 7. Diagrams Illustrating the Top Slicing System of Mining.

cars, or (if in the Winter time) stockpiled for later shipment. A "slice" consists of a room opened up between crosscuts, and may be one, two or more sets wide depending on the tendency of the overburden to crush the temporary timber supports. When the ore has been removed from the room or slice, the supporting timbers are blasted out and the overburden allowed to cave and fill it. Before blasting the timbers, however, boards are laid over the floor of the room to prevent admixture of the caved material with the ore below. While slicing and caving operations are proceeding on the top level, the cross cuts to develop the next level immediately below are being driven, and as soon as considerable areas of cave have been developed on the first level, slicing under these areas is started on the second level. Thus, the entire ore body is mined, slice by slice, and level by level. Levels are generally about eleven feet apart, floor to floor. Haulage of ore on main levels from chutes to shaft may be by hand, mule or electric motor, depending on the size of the mine. On the sub-levels the ore is hand-trammed in small dump cars, or for short hauls, in wheelbarrows, from the slices to the raises.

Advantages of the Slicing System of Mining: The top-slicing-and-caving system has many advantages. It gives a high percentage of ore extraction. If desired, the ore from different working places can be separated, and two or more grades can be produced from the same mine. Development and mining operations are simple and safe, and can be carried out along well defined plans worked out in advance. While the consumption of mining timber is high, cheap inferior grades are used, and under ordinary conditions this item of cost is not excessive. In common with most other systems of mining, it possesses the disadvantage of a limited number of working places; considerable handling of the ore is also necessary.

The Depth of Mine Shafts on the Missabe Range rarely exceeds 350 feet. The average is probably between 250 and 300 feet. On the old ranges, where the rock formations have been folded and tilted, mining operations extend much deeper. Here mine shafts 500 to 1500 feet deep are common, while in some cases mining operations are still in ore at depths well in excess of 2,000 feet.

Grading the Ores: In the early days of iron ore mining, no grading of the ore from analysis, such as prevails today, was made, and the ore was known by the name of the mine that produced it. Then, the number of mines was small, and the ore from any one mine was fairly uniform. As the production increased, however, and the field of available ore was broadened to include deposits previously regarded as unprofitable, it became necessary, in order to simplify shipping, to grade ores according to their composition, and, further, to mix ores differing in composition to produce certain grades. Finally, it became quite common for one mine to ship several different grades, and for the ore from several mines to be grouped under one name. These conditions brought about a necessity

for knowing the exact composition of the various ores, and whether or not, in the case of mixed ore, each cargo was of the grade guaranteed. This grading is done by sampling the ore in the cars as fast as they are loaded at the mine, in lots not exceeding five, and making a rapid but accurate analysis for the determining elements. From this analysis the class or grade of the ore is fixed, and its allotment into a certain group can be made. This is the work of the grader, who, from the analysis of the cars as submitted to him, makes a theoretical shipment in which the contents in silica, iron, phosphorus and possibly manganese, the determining factors in the value of an ore for its particular purpose, must fall within certain predetermined limits.

Transporting the Ores: The Lake ores now supply all the furnaces in Western New York, Western Pennsylvania, Ohio, Illinois, and Indiana, as well as those in the ore producing states of Michigan, Wisconsin, and Minnesota. In order to reach these markets, the ores must be transported for distances varying from 300 to more than 1000 miles, depending upon the locations of both the mine and the furnaces. The cost of transporting this ore by rail alone would be a serious handicap to some furnaces, but fortunately the chain of Great Lakes affords a cheap mode of transportation for the greater part of the long as well as the short distances. Nearly all the ore mined in the ranges, then, goes first by rail to a harbor on Lake Michigan or Lake Superior, where it is loaded on ore carrying boats that carry it either down Lake Michigan to Chicago or Gary or through Lake Huron and Lake Erie to ports further south. For most of the ore, even these lower lake ports are not ultimate destinations, and another haul by rail is required to place it at the furnaces. Now, to return to the grading of the ore, what was there referred to as a theoretical shipment might better have been called a theoretical cargo or boat load. When the cars containing this theoretical cargo, which may weigh from 3000 to 13,600 tons, depending upon the size of the boat, reach the dock at the shipping port, they are unloaded into the dock pockets, one on top of the other, three to six cars to a pocket, in such order as to mix the ore as much as possible. The ore is then allowed to flow from these pockets into the hatches of the steamer, thus, again mixing the ore. Then the boat proceeds to her destination, where the ore is unloaded by electrical, or otherwise operated, grabs, which process of unloading still further tends to mix the ore and make it uniform. All this mixing of the ore is not to be thought of as merely incidental to the operations, but as a necessary course of procedure, for uniformity in the ore is a very important requirement in the successful operation of the blast furnaces. If the ore is unloaded at the works located on the lakes, it is sampled for analysis during the unloading by an elaborate system and is dumped upon its appropriate stock pile; if for inland works, such as Pittsburgh, it is placed in cars and ultimately reaches the works, where each car is sampled, according to printed instructions common to all the works of

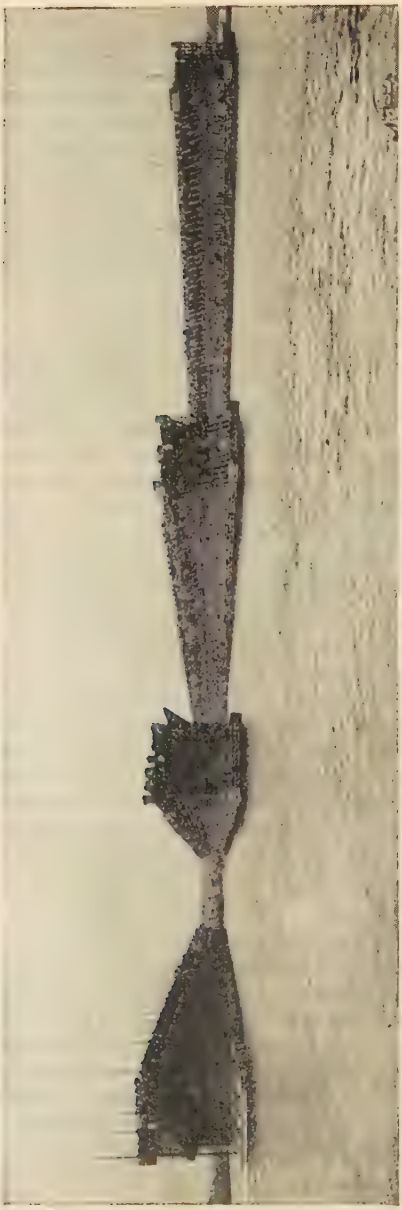


FIG. 8. General View of D. M. & N. Ore Docks, Duluth, Minn.

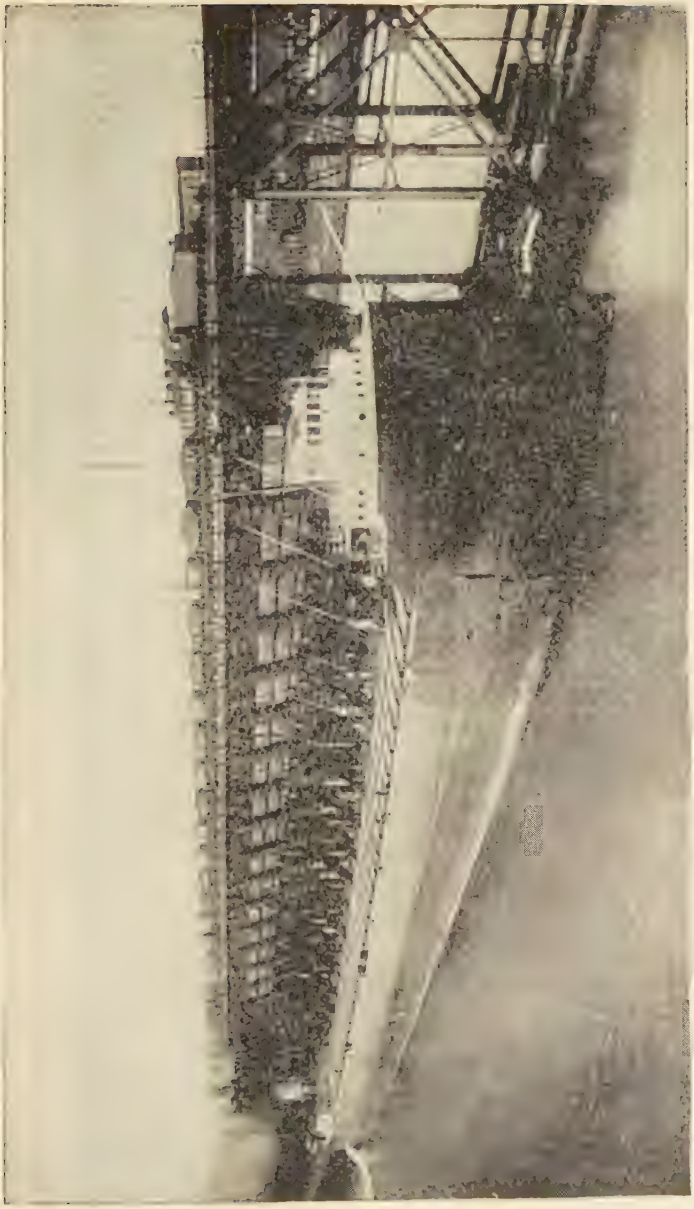


Fig. 9. Loading Ore into Steamer

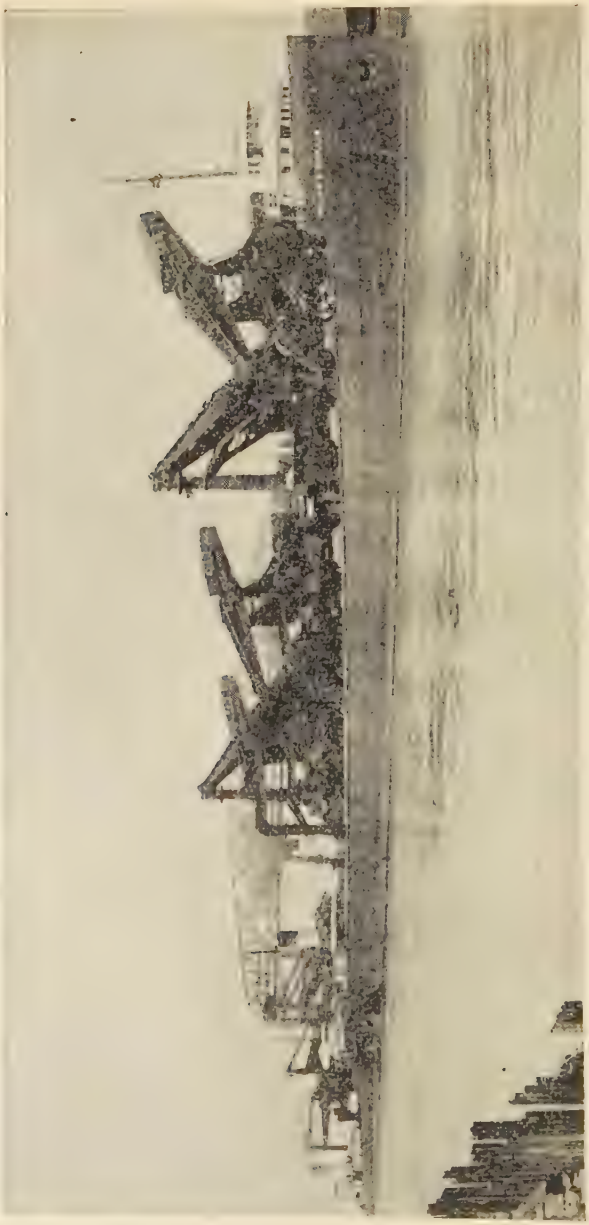


FIG. 10. Unloading Ore from Boats. Showing Hulett Electric Unloaders in operation with ore transfer bridge in the background.

the Steel Corporation. The cars are then unloaded upon a stock pile from which the ore can be used as needed, or directly into the furnace bins, if the ore is needed for immediate use.

Mining and Grading in Winter: In winter the procedure as outlined above has to be changed somewhat. During a part of November, and all of the winter months of December, January, February and March, the ore cannot be transported over the lakes because of the ice. On this account, operations in the open pit mines of the Missabe District are suspended in winter; but in all the underground works, both of the old ranges and the Missabe, mining is continuous throughout the year, and the ore mined during the non-shipping season must be stock piled. As this ore is removed it is carefully sampled, and average samples are analyzed daily. These analyses, supplemented by those made in the work of exploration that is constantly carried on in advance of the mining, make it possible to calculate the average composition of each stock pile at the beginning of the shipping season in the spring. This stock, therefore, may be combined, if necessary, with the ore direct from the mines to make up cargoes of definite and known composition.

CHAPTER IV.

FUELS.

SECTION I.

SOME PRE-REQUISITES TO THE STUDY OF FUELS.

Introductory: There are five basic materials upon which the metallurgical arts depend; namely, ore, fuel, flux, air and water. Of these one is as important as the other, for all metallurgical industry would cease with the failure of any one. At one time all these were thought to be inexhaustible, but recently it has been generally recognized that the supply of the higher grades of ore are limited, and that the more suitable fuels, at the present rate of consumption, must be exhausted in a comparatively short time. Representing the only source of energy under man's absolute control, fuels are the foundation upon which a nation's progress and prosperity depends. The subject is also a very large one. Hence, in this chapter it is desirable to discuss only briefly a few fundamental topics of general interest, and more in detail, a few matters especially important in the iron and steel industry.

Sensible and Specific Heat: Provided no change of state or of allotropic form is involved, the effect produced by imparting heat to a body is a rise in temperature of the body, and if the body is made to give up heat, its temperature falls. This heat, which is easily detected, is often spoken of as **sensible heat.** The quantity of heat required to raise the temperature of a body 1°C. is called its **thermal capacity.** The amount of heat required to raise the temperature of equal masses of different substances 1°C. varies greatly, and the thermal capacity of one gram of any substance, in other words, the number of calories required to raise the temperature of one gram 1°C., is called its **specific heat.** Specific heats are determined by the method of mixtures, which is based on the law of **heat exchange.** This law states that when bodies at different temperatures are brought into contact, exchange of heat takes place until a uniform temperature for all is reached, and that the heat lost by the hotter bodies equals in quantity that gained by the colder ones. The specific heats of a few common metals follow: Iron=.109 cal. Copper=.092 cal. Zinc=.093 cal. Mercury=.033 cal.

Latent Heat and Change of State: Changes of state are governed by the following laws:[1]

Laws of Fusion:

I. "Every crystalline substance begins to melt at a definite temperture, which is invariable for each substance if the pressure is constant."

II. "The temperature of a body of pure substance, when slowly melting, remains constant till the whole mass is melted."

III. "Substances that expand on solidifying have their melting points lowered by pressure, and vice versa."

Laws of Evaporation:

I. "The rate of evaporation increases with rise of temperature."

II. "The rate of evaporation increases with the surface of the liquid exposed."

III. "The rate of evaporation is increased by a continual change of air in contact with the liquid."

IV. "The rate of evaporation is increased by diminishing the vapor pressure, that is, by applying suction to the vessel inclosing the liquid."

Laws of Ebullition:

I. "A pure liquid has a definite boiling point, which is invariable for that liquid under the same conditions."

II. The temperature of the vapor given off by a pure liquid near its surface remains constant till all the liquid is vaporized if the pressure remains constant.

III. "The boiling point of a liquid is raised by salts and lowered by gases dissolved in it."

IV. "The boiling point of a liquid rises with increase of pressure and falls with decrease of pressure."

It will be noted from these laws that when change of state takes place, there is no change in temperature of the body, notwithstanding the constant application or withdrawal of heat. The heat thus involved is sometimes spoken of as **latent** heat, though **heat of fusion** and **heat of vaporization** would appear to be the better terms to employ. The heat of fusion for water is about 80 calories per gram, while its heat of vaporization is 535.9 calories per gram under standard pressure.

Transmission of Heat: Heat is transmitted in three ways; namely, by conduction, by convection and by radiation. **Conduction** is the transmission of heat through a body without visible motion of the body, as through an iron bar. When the heat is transmitted by mechanical motion of the particles of matter, through air or water currents for example, it is called **convection**. The distribution of heat through a blast furnace makes use of these principles. **Radiation** refers to the transmission of heat, independently of matter, by means of waves in the ether. This is the means by which the heat of the sun reaches the earth. These factors are important considerations in the action of furnaces, stacks, ventilators and heating plants.

[1] See High School Physics and University Physics by Henry S. Carhart and Horatio N. Chute, published by Allyn and Bacon, Boston and Chicago.

Fuels and Combustion: Any chemical reaction by which light and heat are evolved is called combustion. In the ordinary cases of combustion, one of the reacting substances is the oxygen of the air. Therefore, fuels are sometimes defined as substances which will burn in air and liberate heat with sufficient rapidity to be applied to practical purposes. The chief elements constituting fuels are carbon and hydrogen, though in certain processes silicon, phosphorus, sulphur, manganese and the metals may serve as fuel. In metallurgy the fuel is often required to act as a reducing agent, in which cases the total heat produced will be derived from two sources, namely, by combustion with oxygen of the air and by combination with oxygen of the ore.

Fuels and Chemical Energy: Fuels represent potential energy, which is given off as heat by chemical action. Therefore, the relations of the weights of fuel, weights of air, and the amounts of heat evolved are fixed quantities. The following reaction furnishes a simple illustration:

$$C+O_2=CO_2+\text{Heat},$$

that is, 12 gm. C + 32 gm. O_2 = 44 gm. CO_2 + 97200 cal. (Heat of formation of CO_2) or 1 gm. C + 2.666 gm. O_2 (11.51 gm. air) = 3.666 gm. CO_2 + 8100 cal. (Calorific power of carbon).

The heat liberated is referred to in two ways. The chemist bases his calculations on the total heat evolved to form a molecular weight in grams of a given substance, in this case, 44 gms. CO_2, which is called the **heat of formation** for that compound. But the metallurgist and engineer employ the heat evolved from a unit weight of fuel, in this case, one gram of carbon, and refer to it as the **calorific power** of the fuel. It should be observed that these terms take into consideration only the total amount of heat evolved, irrespective of the time or speed of the reaction, the duration of which may vary through wide limits. This point is important in the attainment of high temperatures and is connected with the second important factor affecting the combustion of fuels, namely, the temperature to which the products of combustion may be raised by the heat evolved. This is referred to as the **calorific intensity** of the fuels. Both the calorific power and the intensity enter into the valuation of fuels.

Measurement of Calorific Power: As has already been noted, the two practical heat units are the large calorie and the B. t. u. Metallurgists express the calorific power in large calories per kilogram, which is numerically the same as small calories per gram employed by chemists, while engineers use B. t. u. per pound of fuel as the basis of their calculations. The units are readily converted from one to the other; the relation, numerically, between B. t. u. per lb. and Cal. per kilo. is expressed thus:

B. t. u. per lb.: Cal. per kilo. = 1.8 : 1

Hence, to reduce Cal. per kilo. to B. t. u. per pound, it is only necessary to multiply by 1.8. The factor for changing B. t. u. per lb. to Cal. per kilo. is .5555.

The Calorific Power of some common elements in simple oxidation reactions is as follows:[1]

Table 6. Calorific Power of Some Elements.

Element	Reaction.	Calorific Power in Calories per Kilo.
H	$2H_2+O_2=2H_2O$ Liquid	34500
H	$2H_2+O_2=2H_2O$ Vapor	29030
C	$C+O_2=CO_2$	8100
C	$2C+O_2=2CO$	2430
Si	$Si+O_2=SiO_2$	7000
Al	$4Al+3O_2=2Al_2O_3$	7270
P	$4P+5O_2=2P_2O_5$	5895
S	$S+O_2=SO_2$	2196
Fe	$3Fe+2O_2=Fe_3O_4$	1612
N	$N_2+O_2=2NO$	—1541

Calculating Calorific Power: Given the heats of formation of the reacting substances and of the products of combustion, it is possible to calculate the calorific power of some fuels from their analyses. The calorific power of a well made coke can be estimated approximately from the fixed carbon, if the moisture and volatile matter are low.

By analysis, Fixed Carbon=87.0%
Calorific Power of Carbon=8100 Cal. per Kilo.
.87

7047 Cal. per kilo.=calorific power of coke

This calculation for gases becomes more complicated, because the calorific power is usually expressed in Calories per cubic meter or B. t. u. per cu. ft. This fact requires a conversion from weight to volume, since the calorific powers in the table are based on weight. This conversion, however, is a simple matter, since a gram molecular weight of any gas has a volume of 22.32 liters under standard conditions. To find the heat evolved from a gas in calories per liter, it is only necessary to divide the heat of formation by 22.32. In the case of a blast furnace gas composed of CH_4, .2%; CO, 25%; H_2, 3%; CO_2, 12%; N_2, 59.8%; the calorific power may be found as follows: The reactions that may occur in complete combustion are

Reaction (1) $CH_4+2O_2=2H_2O+CO_2$
Heats of formation, 21700 cal.+0=2x58060 cal. +97200 cal.

Reaction (2) $2CO+O_2=2\,CO_2$
Heats of formation, 2x29160 cal.+0=2x97200 cal.

Reaction (3) $2H_2+O_2=2H_2O$
Heats of formation, 2x58060 cal.

[1]See Metallurgical Calculations by Joseph W. Richards, One Volume Edition published by McGraw-Hill Book Company, New York.

From reaction (1) the total heat available from CH_4=

$$\frac{2x58060+97200-21700}{22.32}=8585.+\text{calories per liter.}$$

From (2) available heat from CO=

$$\frac{97200-29160}{22.32}=3048+\text{calories per liter.}$$

From (3) available heat from H_2=

$$\frac{116310}{2x22.32}=2605.+\text{calories per liter.}$$

Total heat of gas available is,

for CH_4 .2% of 8585= 17.17

CO 25% of 3048=762.00

H_2 3% of 2605= 78.16

857.33 calories per liter at 0°C. and 760 m. m. pressure=(857.33 x .11236)=96.33—B. t. u. per cu. ft.

Practical Tests: All calculated results, however, are usually higher than can be obtained in actual practice. Furthermore, with complex fuels, like coals, the composition of which can only be guessed at, it is impossible to make accurate calculations from the analysis, because no account is taken of the heat required to decompose the fuel and gasify the products. Many fuel chemists, however, have evolved formulas by which they are able to determine very closely from the analysis the calorific value of a coal as obtained by laboratory experiment. Nevertheless, experimental methods are relied upon almost wholly to determine the heating power of fuels. These tests may be practical, in which large quantities of the fuel are consumed under conditions approximating closely those of the process for which the fuel is to be used; or they may be laboratory tests, in which small quantities of fuel are burned, and the heat evolved is measured. Practical tests may be made in specially constructed apparatus or under boilers in actual service. These specially constructed apparatus are in the form of large heaters through which water circulates and in which the fuel may be completely consumed. From the amount of fuel consumed, the weight of water heated, the rise in temperature of the water, the difference in temperature between the in-going air and the products of combustion, the calorific power may be accurately determined.

Laboratory Tests: For determining the maximum amount of heat a given fuel is capable of generating, laboratory tests are more exact than

practical tests. Such tests are carried out in specially designed apparatus called calorimeters. There are several makes of these instruments, but the fundamental principles of all are the same. The process consists in completely oxidizing the fuel in a space enclosed by a metal jacket (the bomb) so submerged that the heat evolved is absorbed by a weighed portion of water contained in a perfectly insulated vessel. From the rise in temperature of the water, the heat liberated by one gram of the fuel is calculated. The best types of calorimeters are those called oxygen bomb calorimeters, in which the fuel is burned in the presence of compressed oxygen.

Calorific Intensity: The calorific intensity is more precisely defined as the degree of heat evolved by a given weight of fuel in perfect combustion in air at 0°C. and 760 m. m. pressure. The theoretical maximum temperature depends on the calorific power, and the density and specific heats of the products of combustion, and is inversely proportional to the time required in producing it. In practice the temperature is also affected by the initial temperature of the fuel and air, the amount of air used, amount of water in fuel and air, and by radiation, conduction and convection of materials of the furnace. As the attainment of high temperatures is necessary to many metallurgical processes, all these factors are important, and special devices have been invented to prevent waste, preheat air and gas, and eliminate moisture.

Methods of Conserving Heat: Owing to the high temperature at which the products of combustion escape from furnaces and the large volume of air necessary for the combustion of the great quantities of fuel used, much of the heat generated in the furnace is carried away by the outgoing gases and wasted, unless special methods are employed to recover this waste. This can be done in several ways. The hot gases may be passed through boilers and made to generate steam, conducted into other furnaces requiring lower temperatures, or used to preheat the air and fuel and thus increase the intensity of the heat in the furnace. Since high temperatures are required in most metallurgical processes, the third option is generally selected. The methods by which this preheating is accomplished depends upon two principles, called the **regenerative** and the **recuperative.** In the regenerative method the hot gases from the furnace are conducted through expanded portions of the horizontal flues, almost filled with open brick work, called the "checkers" from the manner of laying the bricks. When the checkers have absorbed heat sufficient to raise their temperature to nearly that of the gases, their connection with the stack is closed, and the air, or air and fuel, if the latter can be preheated, is made to pass through the checkers on its way into the furnace, thus taking on the stored up heat in the checkers. With two such sets of checkers to a furnace this process is made practically continuous by reversing the direction of the gases at short intervals. In the recuperative method the checkers are replaced by a

system of pipes through which the out-going gases must pass. The in-going air, being at the same time drawn in through the space around the pipes, is heated in proportion as the waste gas is cooled.

Pyrometers: The measurement of high temperatures requires special instruments called pyrometers, many of which are made self recording so as to measure continuously the temperature of a furnace through long periods of time. There are many types of these instruments, and only the principles upon which some of the more important types are based will be briefly described.

Specific Heat, or Water, Pyrometer: This is an old type of instrument, and one that is still extensively used. The operation of the instrument is carried out as follows: A weighed amount of metal of known specific heat is placed in a furnace, and when it has attained the temperature of the furnace, it is withdrawn and quickly dropped into an insulated vessel, containing a definite amount of water and provided with a thermometer for reading the temperature of the water. The rise in temperature of the water is proportional to the weight of the ball, its specific heat, and the temperature of the furnace. The first two factors being known, the temperature of the furnace can be readily calculated.

Electric Resistance Pyrometers: Instruments of this type depend on the fact that the electrical resistance of metals increases with rise in their temperatures. In practice the metal will be platinum in the form of wire, which will be inserted in one arm of a wheatstone bridge for measuring resistance. A battery and a galvanometer for detecting difference in potential, both being attached to the bridge, completes the apparatus. In operating the instrument, the slide on the bridge is adjusted so that the resistance of the two arms of the bridge are the same and the galvanometer reading is zero. The "bulb" of platinum wire is now inserted in the furnace, when, the resistance of the platinum wire being increased by the rise in temperature, it is necessary to insert resistance in the other arm of the bridge to keep the galvanometer reading at zero. The amount of the resistance inserted measures the increase in resistance of the wire, which can be interpreted in degrees of temperature.

Thermo-Electric Pyrometers: These instruments are both convenient and accurate, being very simple in construction. They depend upon the fact that if two metals are in contact at a given point, any change in temperature at that point causes an electric current, the intensity of which is proportional to the change in temperature, to flow around a circuit connecting their free ends. This current can be measured by inserting a millevolt meter in the circuit. In practice the metals employed for high temperatures are platinum in conjunction with an alloy of platinum and 10 per cent. rhodium or iridium in the form of wires, which are insulated from each other by means of hollow tubes of refractory materials. For

low temperatures the baser metals may be used, such as iron and nickel-copper alloys.

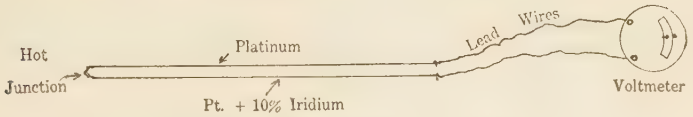


Fig. 11. Diagram of Wiring for Thermo-Electric Pyrometer.

Radiation Pyrometers are based on the law of heat radiation which is briefly stated thus: The energy emitted by a highly heated black body is proportional to the fourth power of its absolute temperature. Such instruments consist of a millevolt meter and a telescope which contains a concave mirror reflector and a delicate thermo electric couple. By pointing the telescope, from a certain distance, toward a highly heated surface, a portion of the radiant heat is made to fall upon the mirror, which concentrates the rays upon the couple, causing it to generate a current that can be measured by the millevolt meter.

Optical Pyrometers depend upon the relation of the intensity of light emitted by an incandescent body and its temperature. In them the intensity of the light from the hot body is compared with that of an incandescent lamp. The simplest form consists of a telescope containing the lamp, and a battery to supply the current. In making a determination, the telescope is pointed at the heated body, and the current is adjusted so that the intensity of light from the filament of the lamp matches that from the body. From the adjustment necessary the temperature of the body is determined. In improved forms of this instrument, a circular plate of colored glass is inserted in the telescope between the lamp and the eye in such a manner that the light from the lamp falls on one-half of this plate and light from the body falls on the other. The two lights are matched by varying the intensity of the light from the body with a diaphragm. A second improvement is made by providing a special rotating prism by means of which the lights from both the body and the lamp are varied in intensity. The amount and direction of rotation necessary to match the lights measures the temperature.

Use of Pyrometers: All modern pyrometers are constructed with graduated scales to read in degrees, so that no calculations for converting the various relations into temperatures are required. All types, however, are subject to errors and require frequent checking and standardization. As a satisfactory description of the operation of all these different types would require a lengthy article, those readers who may be especially interested in temperature control are referred to the published works upon this subject.[1]

[1] Among the best works on pyrometers is the Bureau of Standards Technologic Paper No. 170. "Pyrometic Practice," by Paul D. Foote, C. O. Fairchild, and T. R. Harrison; Price 60 cents; Superintendent of Documents, Government Printing Office, Washington, D. C.

SECTION II.

CLASSIFICATION OF FUELS.

Of the many ways of classifying fuels, that shown below in Table 7 is a very logical and simple one and most convenient for the purposes of this chapter. It requires no explanation.

Table 7. Classification of Fuels.

- Carbon-Hydrogen Fuels
  - Solid
    - Natural
      - Wood: Hard. / Soft.
      - Peat: New. / Old.
      - Lignite: New. / Old.
      - Coal
        - Bituminous: Coking. / Non-coking.
        - Anthracite.
    - Prepared
      - Briquettes.
      - Pulverized Fuels
      - Carbonized Fuels
        - Charcoal.
        - Coke: Beehive. / By-product.
        - Semi-coke
  - Liquid
    - Natural—Petroleum.
    - Prepared: Distilled Oils. / Coal Tar. / Colloidal Fuels
  - Gaseous
    - Natural—Natural Gas.
    - Prepared: Producer Gas. / Blast Furnace Gas. / Coke Oven Gas. / Coal Gas. / Blue Gas.
- Incidental Fuels
  - Bessemer Converter: Iron. / Manganese. / Carbon. / Silicon. / Phosphorus.
  - Sulphur Works: Roasting. / Smelting.

Plan of Study: In discussing the different fuels it does not seem desirable to follow the order of the outline above. Some, like blast furnace and coke oven gases, are best taken up in connection with the processes that produce them, while others, like the distilled oils, are of so little importance from a metallurgical standpoint that they cannot be more than mentioned here. Concerning the others, which play more or less prominent parts in metallurgical processes, it is the intention to dispose very briefly of the less important first, so that the attention may be concentrated upon the more important ones, which will be taken up at the last.

SECTION III.

INCIDENTAL AND LIQUID FUELS.

Incidental Fuels: Under this heading are included all substances which incidentally act as fuels in certain processes. In the acid Bessemer converter, for example, the oxidation of the impurities, silicon, manganese and carbon, to which is added phosphorus and sulphur in the basic converter, furnish heat necessary to keep the metal in a molten state during the blow, and so perform the function of fuels. In the roasting and smelting of pyritic ores the burning of a portion of the sulphur furnishes a great part of the heat necessary for those processes.

Tar: The use of tar as a fuel is of recent origin, and offers a means for the disposal of the excess quantities produced above that required by the tar refiners. Having a low ash and sulphur content, it is well suited chemically for use as open hearth and heating-furnace fuel. It is a viscous fluid at ordinary temperatures. Hence, it must be kept at a relatively high temperature both in the storage tanks and feed lines. This heating is accomplished by means of steam pipes immersed in the tar. Special burners, one type of which is shown in the accompanying figure, of the steam or air injector type are required to burn tar properly. Tar carries in suspension a great many small carbonaceous bodies, and on standing, especially at the lower temperatures prevailing in storage tanks, these grow into pitch-like bodies of considerable size, which clog up the burners and the small pipe lines of the system. Its calorific power is between that of coal and oil, 16000—18000 B. t. u. per pound. This fact, coupled with its low cost due to the increased production, tends to stimulate efforts to use it wherever possible.

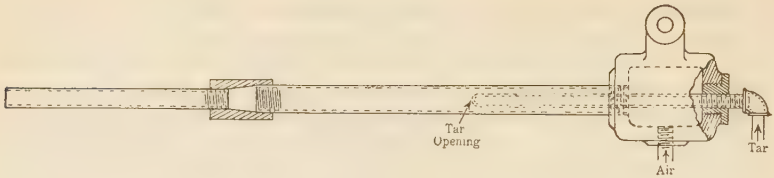


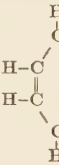
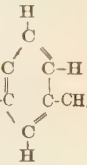
Fig. 12. One Type of Tar Burner.

Petroleum: The only natural liquid fuel, and a material of the highest commercial importance, is petroleum, a product obtained from reservoirs deep in the earth. Its heating power is much greater than that of coal, (The calorific power of crude petroleum=21000 B. t. u. per pound, Coal= 9000 to 15000 B. t. u. per pound) and it is obtained in immense quantities. On distilling, it yields a high percentage of very valuable oils. On this account it is used as a metallurgical fuel only where coal is scarce and high in price. In using the oil special burners are required, as it must be vaporized or atomized and properly mixed with air to insure complete combustion.

Composition of Petroleum: Petroleum is a very complex mixture of organic compounds. In small amounts it contains compounds of oxygen, sulphur, and nitrogen, but principally it is composed of compounds of carbon and hydrogen. Its content of the former element varies from 84 to 87 per cent., and of the latter, from 11 to 13 per cent., depending upon the locality from which it is obtained.

Hydrocarbons—Generalized, Empirical and Structural Formulas: These compounds of carbon and hydrogen found in petroleum are called hydrocarbons. They are numbered by the hundred, and a study of their composition has shown that they fall into a number of homologous series which may be represented by generalized formulas as shown in Table 8. In representing these compounds, the empirical, or simplest, formulas are often found inadequate, because it frequently happens that two different compounds will have the same empirical formula, and that in many compounds the valence of carbon is apparently not a whole number. To overcome this defect, the structural formula, which aims to show how the molecules are built up, was invented. In these formulas the valence of carbon, which is represented by —'s, called valence bonds, is assumed to be four in all cases, and it is also assumed that the atoms of carbon have the power of uniting with each other to form nuclei to which other elements may attach themselves. These formulas are also illustrated in the following table:

Table 8. The Different Homologous Series of Hydrocarbons.

Generalized Formula of Series	Names Applied To Series	Names of First Compound of Series	Empirical Formula	Structural Formula	Formula of Second Member
C_nH_{2n+2}...	Methane, Paraffine or Chain Series.	Methane Marsh Gas Fire Damp	CH_4		
C_nH_{2n}.....	Olefine, Ethylene, Unsaturated Open Chain Series.	Ethylene.	C_2H_4		
C_nH_{2n-2}....	Acetylene Series.	Acetylene.	C_2H_2		
C_nH_{2n-4}....	First member unknown.				
C_nH_{2n-6}.....	Benzene,–Aromatic or Closed Ring Series.	Benzene.	C_6H_6		
C_nH_{2n-8}.....	Not many members discovered.				
C_nH_{2n-10}...	Not many members discovered.				
So on to....					
C_nH_{2n-32}...	Not many members discovered.				

Hydrocarbons of the series C_nH_{2n+2} make up the greater portion of the paraffine base of petroleums, as is indicated in Table 9. Members of the series C_nH_{2n} are also constituents of many petroleums, while only a few of the higher members of the series C_nH_{2n-2} and C_nH_{2n-4}, have been found in oils west of Pennsylvania. The aromatic series, C_nH_{2n-6}, occur in small amounts in nearly all petroleums. Occurrence of members of the other series is somewhat rare in petroleums, and are in small amounts when found at all.

Fuel Oil and Other Products of Petroleum: The increasing demand for gasoline and other petroleum products makes it very undesirable that crude petroleum as obtained from the wells be used for fuel. Besides, gasoline in a fuel oil is dangerous on account of the increased danger of explosions its presence entails. Fuel oil, then, is a very indefinite term that is applied to any product of petroleum used for the production of heat or power. There are no fixed specifications for it, and consumers order it to suit their requirements. The usual grades have a calorific value of about 135000 B. t. u. per gallon. The products from many of the oil refineries west of the Mississippi River are gasoline, naphtha, kerosene and fuel oil, while Eastern refineries usually carry the fractionation of the oil much farther, their output being such products as gasoline, benzine, naphtha, kerosene, light machine oil, automobile oils, cylinder oils, paraffine wax and tar, pitch, or coke.

SECTION IV.

GASEOUS FUELS.

Advantages of Gaseous Fuels: The many advantages possessed by gaseous fuels make them ideal for many purposes. Owing to their gaseous state, they require no labor in handling, and their freedom from foreign matter eliminates ash and danger of contamination. As the temperature is easily controlled, and the flame can be directed wherever desired, the working conditions of a furnace may be kept very uniform. The kindling temperatures of gases lie between 585° C. and 750° C., and the speed of combustion at these temperatures is practically instantaneous, which fact makes it easy to attain very high temperatures.

Table 9. The Paraffine Series of Hydrocarbons, the Members of which are found in Natural Gas and Petroleum of the Western Pennsylvania District.

State at Ordinary Temp.	Name	Empirical Formula	Melting* Point Deg. C.	Boiling* Point Deg. C.
Gases:	Methane	CH_4	—184.0	—165.0
	Ethane	C_2H_6	—171.4	— 93.0
	Propane	C_3H_8	—195	— 45.0
	Butane	C_4H_{10}	—135	+ .1
Liquids:	Pentane	C_5H_{12}	—130.8	36.3
	Hexane	C_6H_{14}	— 94.0	69.0
	Heptane	C_7H_{16}	— 97.1	98.4
	Octane	C_8H_{18}	— 56.5	125.5
	Nonane	C_9H_{20}	— 51.0	150.0
	Decane	$C_{10}H_{22}$	— 31.0	173.0
	Undecane	$C_{11}H_{24}$	— 26.0	195.0
	Dodecane	$C_{12}H_{26}$	— 12.0	214.0
	Tridecane	$C_{13}H_{28}$	— 6.0	234.0
	Tetradecane	$C_{14}H_{30}$	+ 5.0	252.0
	Pentadecane	$C_{15}H_{32}$	10	270.0
	Hexadecane	$C_{16}H_{34}$	18.0	287.0
Solids:	Octadecane	$C_{18}H_{38}$	28.0	317.0
	Eicosane	$C_{20}H_{42}$	37.0	.....
	Tricosane	$C_{23}H_{48}$	48.0	.....
	Tetracosane	$C_{24}H_{50}$	51.0	.....
	Pentacosane	$C_{25}H_{52}$	53–54.0	.....
	Hexacosane	$C_{26}H_{54}$	55–56.0	.....
	Octocosane	$C_{28}H_{58}$	60.0	.....
	Nonocosane	$C_{29}H_{60}$	62–63.0	.....
	Hentriacontane	$C_{31}H_{64}$	68.0	.....
	Dotriacontane	$C_{32}H_{66}$	70.0	.....
	Tetratriacontane	$C_{34}H_{70}$	71–72.0	.....
	Pentatriacontane	$C_{35}H_{72}$	75.0	.....

*See American Petroleum Industry by Raymond F. Bacon and William A. Hamor, Published by McGraw-Hill Book Company, New York. Also Organic Chemistry by A. F. Holleman, Fourth English Edition, published by John Wiley & Sons, Inc., N. Y.

Natural Gas is the most remarkable fuel of all. Found in the earth under high pressure and free from non-combustible gases, it represents a perfect fuel. Upon being regenerated it undergoes partial decomposition and is, therefore, never preheated, but with it the highest temperatures that are practical are easily obtained by proper manipulation. The supply of this gas, formerly thought to be inexhaustible, is now declining rapidly, and this fact, combined with its demand for domestic purposes, is forcing its use in the metallurgical and other industrial arts to be abandoned. Geologically, natural gas is closely associated with petroleum and undoubtedly is of similar origin. It is composed of the lower gaseous hydrocarbons of the paraffine series, mainly methane.

Artificial Gases are manufactured from coal. The method of manufacture depends on the end sought. Thus in retort gases—coal gas and coke oven gas—only the volatile products of the coal are utilized for gas, while in the gas producer the whole combustible substance of the coal is converted into gas. Of these, coal gas and coke oven gas most nearly approach natural gas in calorific power and efficiency. Producer gases always contain a high percentage of non-combustibles. The advantages in favor of the producer are that an otherwise poor fuel may be converted into a desirable one, and that all of the fuel is gasified. As to blast furnace gases, their utilization under boilers, in gas engines, and in blast furnace stoves represents a saving that amounts to millions in a single year. A detailed account of this fuel will be taken up later. Table 10 below shows useful data in comparing the various gaseous fuels.

Table 10. Composition of Gaseous Fuels.
Representative Analyses
Per Cent by Volume

	Natural Gas		Coke Oven Gas	Bench or Coal Gas	Carburetted Water Gas	Water or Blue Gas	Producer Gas		Blast Furnace Gas
	#1	#2					#1	#2	
Carbon Dioxide, CO_2	.2	.2	1.7	2.0	3.0	3.8	5.0	10.6	12.9
Illuminants (as C_2H_4)	.4	.5	3.0	3.7	10.0	0	.2	.4	0
Oxygen, O_2	0	.3	.1	.8	.5	.5	0	0	0
Carbon Monoxide, CO	0	.5	3.5	7.5	34.0	43.1	25.6	17.6	26.3
Hydrogen, H_2	0	0	53.9	48.5	35.5	47.5	10.2	11.8	3.7
Methane, CH_4	77.7	94.5	34.6	33.0	12.0	.8	3.8	4.4	0
Ethane, C_2H_6	19.4	0	not det'd	not det'd	not det'd	0	0	0	0
Nitrogen, N_2	2.3	4.0	3.2	4.5	5.0	4.3	55.2	55.2	57.1
*Net B.t.u. per cu.ft.	1027	868	518	512	465	277	148	135	94.8
Gross " " " "	1134	963	583	573	505	301	157	146	96.7
Sulphur per 1000 cu.ft.	0	0	.8 lbs.	not det'd	not det'd	0	.1 lbs.	.15 lbs.	0

*Does not include the latent heat of the water formed in combustion.

Principle of the Gas Producer: While there are many different types of gas producer, the apparatus is essentially a vertical cylindrical shaft, lined with fire brick, partially filled with coal when in use, through which, in modern practice, steam and air are forced upward from the bottom, where combustion of the non-volatile part of the coal is continuous. In its upward passage, the carbonic acid gas formed by the combustion of the carbon of the coal is reduced, in part, by the incandescent fuel, forming carbon monoxide. Part of the steam is also acted upon by the hot coke, form-

ing carbon monoxide and free hydrogen, and some methane is obtained from the distillation which the coal undergoes at first. As it is ordinarily operated, the producer gives a gas which may vary in composition about as follows:

Carbonic Acid, CO_2,...	5 to 9%
Carbon Monoxide, CO,	18 to 27%
Methane, CH_4,.....	2 to 4%
Hydrogen, H_2,.....	10 to 18%
Nitrogen, N_2,.....	48 to 55%

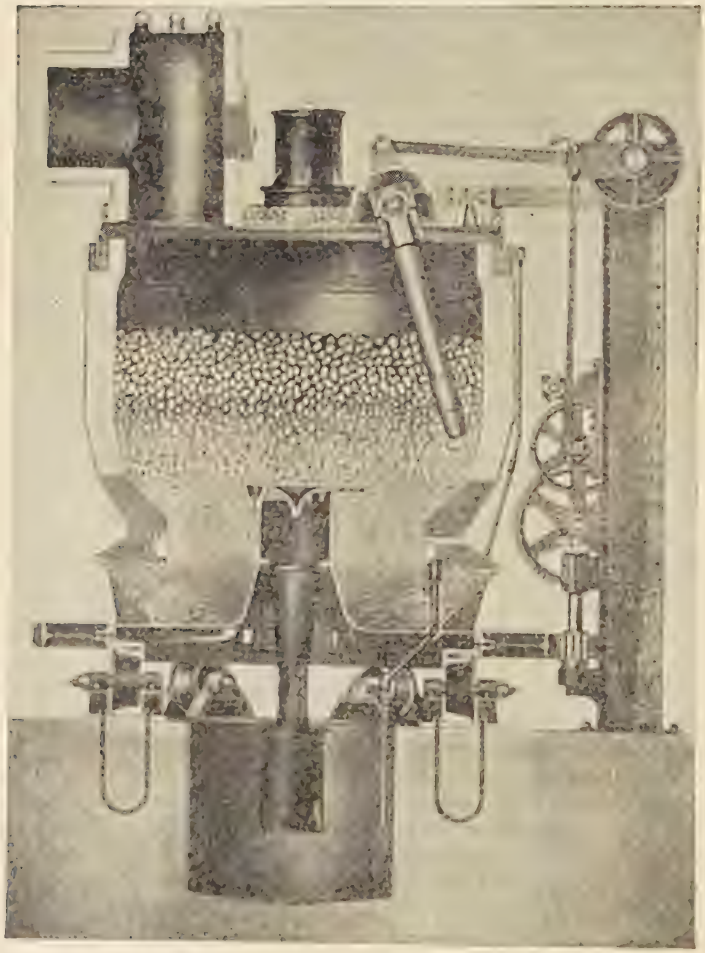


FIG. 13. Sketch. Section Through Gas Producer.

Factors Affecting the Efficiency of the Producer: The greatest efficiency of the gas producer is attained when all the oxygen of the injected air is caused to combine with carbon to form only carbon monoxide, provided the excess heat thus generated is also made available. In practice these results are never accomplished entirely, but efforts to attain them have revealed the fact that they can be most nearly approached by carefully regulating the temperature, by maintaining perfect uniformity of the working conditions, and by injecting steam with the air. All these objects are accomplished in fairly efficient degree in the Hughes mechanically poked producer, a brief description of which follows:

The Hughes Producer as an Example of Mechanically Poked Producer: This producer, a vertical section of which is illustrated in the accompanying sketch, is a cylindrical steel shell, 5/16 inch thick, lined with 9 inches of first quality fire brick, and closed at the ends with water sealed tops and bottoms. When ready for use it sits with its base resting on five wheels which are mounted on a frame carried on a concrete foundation. By means of gears connected to a driving mechanism, it is rotated over these wheels, the speed of rotation when in use being 1/10 r. p. m. The top plate is a steel casting riveted to the charging floor, under which the producer itself revolves. It contains the openings for the gas outlet, the hoppers, the poker and the observation holes. There are two hoppers, through which coal is fed to the producer, one on each side of the outlet, but they are at different distances from the center of the producer to help provide even distribution of the coal. A bell valve closes the base of the hopper, and when this bell is dropped to dump the coal into the producer, the hopper may be closed by sliding a circular plate over its top. There are several holes three inches in diameter at various points in the top seal for observing the condition of the fire, and for poking out clinkers; these holes are closed with water sealed caps. The poker is a round hollow steel casting with a forged steel tip. It is six feet in length and tapers from eight inches in diameter at the top to five inches at the tip. The poker and its trunnions are water cooled, the water being admitted through the trunnions, then passing through the poker to the top plate which is covered with the water to a depth of five inches. From the top plate the water flows to the top seal, or trough, around the top plate, then through a drain pipe to the water seal in the ash pan. The top of the poker is enclosed in a gas tight mounting, and is so mounted that the poker is swung back and forth through an arc of about 35° by means of eccentric connections from the producer rotating mechanism. A full stroke of the poker carries its tip from the center to the side wall of the producer, and is timed to occupy 3.21 minutes, thus allowing 3.1 strokes in one revolution of the producer. The result of the rotating motion of the producer and the backward and forward action of the poker is to produce a series of semi-ellipses, so that the poker covers, in a period of 70.72 minutes, or 22 strokes, practically the entire area of the

shell. The bottom of the vessel serves as an ash pan, which must also be water sealed. To form this seal the bottom is made in the form of a circular trough, which is attached to the main shell of the vessel so that its outer rim, or lip, extends several inches beyond this circumference of the shell. Into this trough the sealing shell of the producer projects to within five inches of the bottom. Since this construction leaves the central portion of the bottom within the producer somewhat cone shaped, the ashes are deflected toward this five-inch opening at the bottom of the trough, where they may be removed through the water which flows from the top and fills the trough to prevent the escape of gases. The steam blower is inserted through the center of the bottom and extends some twenty inches into the producer, where it is capped by a conical hood to prevent it from becoming choked with the ashes. The mixture of steam and air is admitted just beneath this hood through three rows of small openings to provide for equal distribution of the blast. The ratio of steam and air is controlled by the openings at the bottom of the blower, but the quantity of the mixture admitted to the producer is regulated by the steam pressure, which may be changed at will by the operator from the charging floor.

Conditions and Reactions: An understanding of the principle and the operation of the producer is much clarified by a study of the reactions and conditions prevailing in it while it is in use. A study of the conditions show that there are three zones or belts of action in the producer, known as the distillation or top zone, the reaction, or middle, zone, and the combustion, or bottom, zone. Then, below these zones is the inactive, or ash, zone. Thus, upon being charged into the producer, the raw coal is first subjected to a distillation very much as in the process of coking. In this top zone the volatile products are driven off, and the coal is converted into a kind of coke, which will have then reached the reaction zone. Some of this coke, passing through the reaction zone unchanged, reaches the region just over and around the hood of the blower. Here it meets the incoming air, and having been heated to above the kindling temperature, combustion takes place, whereby all the remaining carbon is consumed according to this simple reaction, $C+O_2=CO_2+heat$. The carbon dioxide gas thus generated, together with the undecomposed steam and other gases, rises at once into the reaction zone. Here the coke, having been heated to a high temperature from the heat liberated by the above reaction, acts as a reducing agent toward both carbon dioxide and water, thus, $CO_2+C+heat=2\ CO$ and $H_2O+C+heat=H_2+CO$. It will be noted that both these reactions absorb heat, but that only the second is under control and, hence, available for lowering the temperature in the producer. The reduction of all the CO_2 formed in the combustion zone has never been brought about, so that a small quantity is always present in producer gas. The relative amounts of CO, H_2 and CO_2 in the final gas depends to a great extent upon the manipulation of the producer. As to the other com-

ponents of this gas, the nitrogen, being introduced with the oxygen as air, cannot be controlled, while the hydrocarbons such as CH_4 and C_2H_4 represent products of the distillation.

Operation of the Hughes Producer: The ideal conditions in a Hughes producer are realized when the combustion zone extends to about a foot above the top of the blower hood; when the reaction zone is from one and one-half to two feet thick; when the distillation zone is from one-half to one foot thick; when the conditions are such that the ash, the coke and the coal occur in level zones; and when the amount of air and steam are so adjusted that the fuel is properly burned without excess of any of the undesirable components in the final gas. The necessary air is injected into the producer by a steam jet. Thus the steam serves the two-fold purpose of injecting the air and of controlling the temperature in the producer by absorbing heat, during its decomposition, which later appears as potential energy in the gas. This lowering of the temperature, combined with the disintegrating effect of the steam upon the ash, tends to prevent clinkering. If too much steam be used, the temperature in the reaction zone will drop below normal, the CO will be low and the percentage of hydrogen will be high. This condition causes the gas to burn with a short, intense, non-luminous flame that has a detrimental effect upon the brick work of the furnace in which it is used, especially upon the ports and roof of the open hearth furnace. But the judicious use of steam may increase the efficiency of the producer to 80 or 85 per cent. of the heating power of the fuel. The experienced operator judges the quality of the gas by its appearance, striving for a dense yellowish blue gas. The greatest trouble in operating arises from the accumulation of unburned carbon and fine ash in the mains, which must be cleaned out at regular intervals. The mains are brick lined and are fitted with numerous dust catchers, or man holes, to afford access for cleaning.

SECTION V.

THE SOLID NATURAL FUELS.

Analysis of Solid Natural Fuels: Upon examination all the solid natural fuels are found to consist of combustible and non-combustible materials. The combustible portion is composed mainly of carbon and hydrogen, and the constituents of the non-combustibles are water and a mixture of mineral substances called ash. By the gradual application of heat without access of air, the water is first expelled, which is followed closely by the combustible volatile matter, and there remains a non-volatile mass composed of carbon, called fixed carbon, and ash. Upon admitting air, the fixed carbon burns readily, leaving only the ash. A similar process carried out so as to determine the amounts of these four classes of materials is called a **proximate analysis.** There are two general methods for making a proximate analysis, depending upon whether or not it is desired to separate

the volatile matter into its constituents. These are often referred to as the American and the European methods, the latter being also called the **progressive distillation method.** The determination of the percentages of the various elements present in the fuel constitutes an **ultimate analysis.** The following analysis of a coal by each of these three methods will illustrate all the points mentioned, and help to show the importance of the chemical analysis.

Table 11. Analysis of a Solid Fuel, Coal, by the Three Different Methods.

Proximate Analysis, American Method	Ash	7.16%	Proximate Analysis, Progressive Distillation Method	Coke	Ash 7.160%
	Fixed Carbon	59.98			Carbon 59.980
	Volatile Matter	32.86		Tar	5.420
	Total	100.00%		Free NH_3	.285
	Total Sulphur	1.02%		Comb. NH_3	.041
	Phosphorus	.005%		Moist	4.765
				Volatile Sulphur	.313
				Light Oil	1.353
				Gas	20.686
				Total	100.003%

Ultimate Analysis	Ash	7.16%
	C	79.41
	H	5.14
	N	1.46
	O	5.81
	S	1.02
		100.00%

Wood: This very interesting substance is composed mainly of cellulose, $C_6H_{10}O_5$, a compound formed in the tree or plant from water taken up from the soil and carbon dioxide from the air. The change is wrought mainly in the leaves of plants through the agency of sunlight. Wood, then, represents potential energy, the original source of which is the heat from the sun, and it, in turn, is the source of all the natural solid fuels. It was the first fuel used by man, and for centuries was the principal one. In metallurgy it has been supplanted by coal, though for some purposes it is still used, mainly in the form of charcoal obtained by the destructive distillation of wood. The calorific power of dry wood is about half that of good coal.

Peat is of little value as a metallurgical fuel. It finds extensive use in Europe as a domestic fuel, and the better grades may be successfully employed in gas producers. Its chief interest lies in the fact that it is the first step in the formation of coal. Peat results from the decomposition of wood substance out of contact with air. It is formed in swamps and marshes from water plants of all kinds such as algae, mosses, sedges, rushes, reeds, shrubs, like willows, and even trees. A species of moss called sphagnum is especially important in the formation of peat. It grows on the surface of still and shallow waters with only a small portion in air, and as it grows the submerged portion extends farther and farther beneath the surface until the bottom is reached. Starting growth near the shore of shallow lakes, it gradually extends into a lake until the whole basin is filled with soft carbonaceous matter, and a bog results. This growth is followed by larger growths, until the former lake is packed with carbonaceous matter. The accumulation being submerged, the carbon compounds of the plants are slowly decomposed, by which process the carbon is isolated, though a part escapes with hydrogen and oxygen as marsh gas and carbon dioxide. The reaction is represented thus:

$$6C_6H_{10}O_5 = 7\,CO_2 + 3\,CH_4 + 14\,H_2O + C_{26}H_{20}O_2$$

Cellulose or Wood Substance	Carbon Dioxide	Marsh Gas	Water	Peat Substance

In certain geological periods, particularly the carboniferous, the conditions being more favorable for plant growth of this kind, the processes described proceeded more rapidly than at present, with the result that marshes of great depth and area were filled with vegetable growths. These carbonaceous deposits were subsequently submerged through vertical movements of the earth's crust, in which position they became covered by deposits of sedimentary rocks. Later movements of the earth's crust raised many of these deposits up out of the sea. In the meantime the peat had been changed into coal.

Lignite and Brown Coal, geologically and chemically, occupy positions intermediate between peat and coal. They were formed between the Quaternary and Jurassic periods and are widely distributed. They have low calorific power, and some kinds contain as much as 15 per cent. of water. They are sharply distinguishable from peat, but grade into coal so gradually that no one has attempted to distinguish between the oldest lignite and the youngest coal. The relation between vegetable and mineral fuels are more clearly shown by the accompanying table (12) and diagram (Fig. 14).

Table 12. Approximate Analyses of the Different Solid Fuels.

	Air Dried Wood	Air Dried Peat	Lignite	Bituminous Coal	Anthracite Coal
	%	%	%	%	%
Vol. M....	42–40	30–60	30–45	20–45	.5–6
Fixed C....	39–41	11–40	45–50	40–85	85–92
Ash.....	.15–2	3–75	4–15	4–20	2–15
Moisture or Water....	20–25	6–20	10–15	1–6	.5–4
C. P. (Cals. per Kilo.)	4600–5000	2000–5000	3000–6000	7000–9000	9000–9500

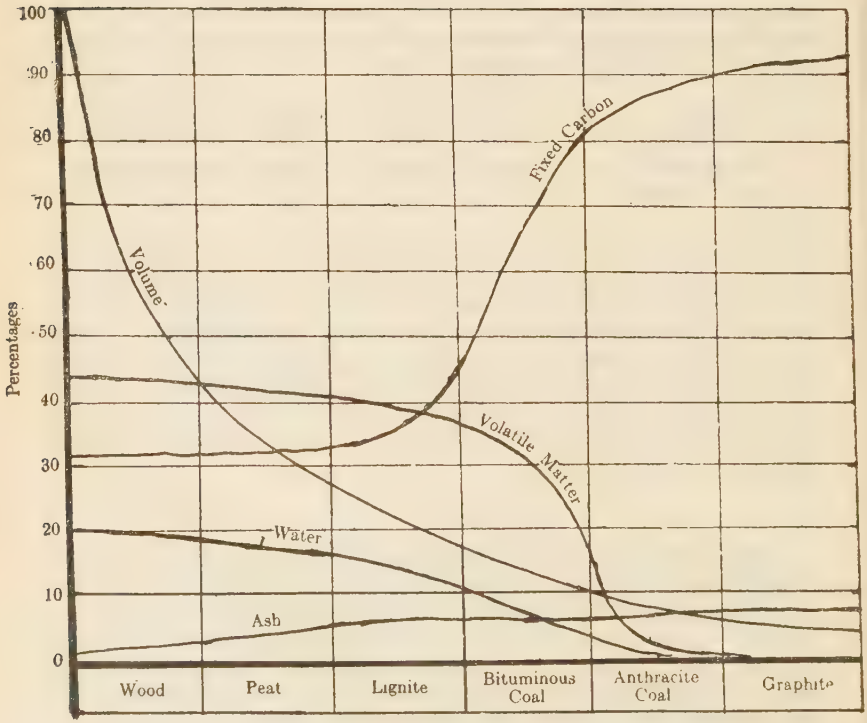


Fig. 14. Graphic Representation of Transformation of Fuels.

Eras and Kinds of Animals	Periods and Chief Events	Order of Strata	Deposits of Valuable Minerals
Cenozoic (Mammals)	Quaternary Glaciers in N. E.		Peat in East Lignite in West Petroleum in Tex. and Lou.
	Tertiary		Lignite in West Gold and Silver in West
	Rocky Mountains		Oil and Gas in Wyo. and Cal
Mesozoic (Reptiles)	Formed		Lignite in West
	Cretaceous		Chalk in So. W.
	Rapid Erosion, West		Petroleum in Cal., Wyo., Tex., Colo. and La.
	Mountains West		Potomac Carbon Rock Petroleum in Wyo.
	Jurassic		Limestone—Wyo. and Utah
	Warping of Surface E		
	Triassic		Coal in Va. Petroleum in Wyo.
Palaeozoic (Fishes)	Slow Folding East		Rock Salt of Texas Petroleum both East and West
	Surface Alternately Rises and Sinks		Coal Coal Coal
	Carboniferous		Coal Coal Coal Coal Coal Coal } Pennsylvania District
	Sea Advance		Gypsum Limestone in Middle West
	Sea Retreats		Oil, Gas—Pa., W.Va., O., N.Y. Ind.
	Devonian		Limestone, East Limestone, East
	Sea Advances		Sand Stone
	Sea Retreats		Limestone, East Clinton Iron Ores, Ala. Oil-Gas in N. Y., O., Ind., Ill. and Ky.
	Silurian		Rock Salt in N. Y.
	Land Submerged		Limestone Zinc and Lead
(Molluscs)	Cambrian		Sand Stone Limestone
	Land Submerged		
Archaean (Lowest Forms)	Huronian		Limestone Lake Superior Iron Ores
	Laurentian		Graphite Igneous Rock

Carboniferous Period
Coal Beds
of
Western Penna. District

Relative Position	Name	Thickness Max.	Thickness Min.
246′	Waynesburg	10 ft.	6 in.
49′	Sewickley	6 ft.	3 ft.
39′	Redstone	6 ft.	3 ft.
630′	Pittsburgh	9 ft.	5 ft.
1344 Ft.	Upper Freeport	8 ft.	3 in.
71′	Lower "	5 ft.	? in.
53′	Upper Kittanning	4 ft.	"
19′	Middle "	3 ft.	"
30′	Lower "	8 ft.	"
54′	Clarion	2 ft.	"
30′	Brookville	5 ft.	"

FIG. 15. Diagram Depicting Geologic Periods in which Gas, Oil and the Valuable Minerals are Found in the United States.

Coal: This mineral, on account of its availability, adaptability, and high calorific power, has become the chief source of energy at the command of man. Used both in its natural state and in prepared forms, it constitutes the chief metallurgical fuel; and the high state of development of certain processes, like that of the blast furnace, for example, have been possible only through the peculiar properties of this remarkable substance. Its origin and history is as remarkable as its properties, and though these subjects belong to geology, they are of interest to the metallurgist because they emphasize the need of conserving the fuel. While it has been deposited in immense amounts, the supply is exhaustible and practically fixed, since the rate of consumption is many times the rate at which it is being formed. In this connection a study of Fig. 15 will be found interesting.

Bituminous Coal: All coal in the natural state may be looked upon as being composed of coal substance, ash, and hydroscopic water. Bituminous coals, on account of their peculiar properties, are the chief source of metallurgical fuels. The coal substance of these coals is decomposed by distillation into carbon and a mixture of volatile compounds. During this process some kinds fuse into a pasty mass, leaving at the end, when all volatile matter has been expelled, a strong but porous mass called **coke.** It is not known what the coking properties of coals depend upon. Coals very much alike in physical appearance and chemical composition may show widely differing coking qualities, while others differing in both these respects produce cokes of equal quality. During the coking process, some coals expand while others contract. This point is an important one in by-product practice, because expansion wedges the coke in the oven, making it difficult to remove, and causing damage to the oven walls.

Ash in Coal: The ash in coals is also an important factor in their valuation. Aside from decreasing the calorific power, it affects the coal in other ways. In steam coals the composition of the ash may be such that it fuses at a low temperature, thereby forming large clinkers; or it may be practically infusible, resulting in no clinker, with the result that a suitable bed of coals cannot be kept on the grate, due to the fineness of the ash. To cite a concrete example, a certain coal in the Pittsburgh District produced ash of approximately the following composition: SiO_2, 45%; Al_2O_3, 24%; Fe_2O_3, 21%; CaO, 7%; MgO, 2%; P_2O_5, .6%. Such an ash is moderately fusible, and so is most desirable. In the ash is found the phosphorus, which determines whether coke made from a certain coal shall be used for making Bessemer or basic iron. The sulphur is also important. In coal, it is present as organic and iron sulphide. In coking, about half of this sulphur is given off with the volatile products, and about half remains in the coke as FeS or Fe_7S_8 and S. When the coke is burned these substances are completely changed, the iron being oxidized to FeO, or Fe_3O_4 and the sulphur to SO_2. Often a seam of good quality coal is divided or cut horizontally by deposits of slaty material known as bone

coal, binder, horse back, etc., all of which must be mined with the coal. Where these conditions exist to any considerable extent, it is necessary to clean the coal by picking, jigging, or washing. As a rule the purest coal is in the middle of the seam. Phosphorus in particular occurs mainly at the top. The top and bottom will always contain the highest percentages of ash and sulphur.

SECTION VI.

PREPARED SOLID FUELS—POWDERED COAL AND COKE.

Pulverized Coal: The prepared solid fuels chiefly employed in the iron and steel industries are pulverized coal and coke. Briquettes and semi-coke are seldom, if ever, met with, and, while charcoal is still used in blast furnaces to make certain special grades of pig iron, the furnaces using this fuel are small and few in number. By the term pulverized coal is meant coal in the most finely divided state it is practicable to produce it. Crushed coal, granulated coal, and powdered coal are terms used to designate the less finely divided material. Powdered coal and pulverized coal are sometimes used interchangeably, but the tendency is to restrict the former term to material somewhat coarser than the pulverized. While there is no established standard, it is generally assumed that, to be classed as pulverized, the fuel should be reduced to such a degree of fineness that at least 85 per cent. will pass through a 100-mesh sieve. The degree of fineness varies according to the kind of coal and the purpose for which the fuel is used. Thus, with high volatile bituminous coal for open hearth furnaces, at least 95 per cent. should pass through a 100-mesh sieve, and 80 per cent. through a 200-mesh.

Uses of Pulverized Coal: Though first attempted about 100 years ago, no progress was made in the use of finely divided solid fuels until recently, owing to the difficulties of securing the proper conditions for their preparation and combustion, and also to the abundance of other desirable fuels. The first notable development in this country was in connection with the firing of rotary cement kilns. Powdered coal was first used for this purpose about 1895, and its application was confined largely to this field until 1914, when the shortage of natural gas, the great demand for petroleum products and other conditions began to force the consumers of fuels to seek new fuels or more efficient methods of burning coal. Since the latter date, the development of finely divided solid fuels has been remarkably rapid, with the result that they have been applied to a great many purposes, including, besides the clinkering of cement, the roasting and drying of ores, the burning of lime in rotary kilns, the smelting of copper and lead; and the firing of boilers, reheating, forging and annealing furnaces, sheet and pair furnaces, tinning and galvanizing pots, reverberatory furnaces of various kinds, and open hearth furnaces. In fact, it has been found adaptable for use wherever large amounts of fuel are consumed.

Advantages of Pulverized Coal: So far as combustion is concerned, the burning of finely pulverized coal presents features similar to those encountered in burning gases. When mixed with air and ignited, it explodes, and when it is injected into a heated chamber with a sufficient quantity of air, complete and rapid combustion approximating that of fuel oil, or the fuel gases, ensues. To insure complete combustion, however, the dust must be injected into the furnace mixed with a certain amount of air, and the velocity of the gases through the chamber must be relatively low or their path through the chamber relatively long, because the combustion rate of the dust is somewhat lower than that of the gases. The chief problems in developing its use were to design a machine or machines that would pulverize the coal to the desired degree of fineness rapidly and cheaply; to evolve a method of handling,—transporting and storing,—the dust safely and economically; and to design a system of feeders and burners that would meet all the requirements for complete combustion and give positive control of the amount of coal consumed. All these problems have now been solved, so that it is controlled almost as readily as gases, and handled as safely and practically as easily as fuel oil, while the cost of preparing it is less than that for the production of an equivalent amount of producer gas from the same grade of coal.

The Disadvantage of Pulverized Coal, as compared with liquid or gaseous fuels, is due to its ash content. At high temperature this ash fuses, forming tiny globules; at lower temperatures, only a portion, depending upon the temperature of furnace and the fusibility of the ash of the coal, will fuse. In all cases a greater or less amount of this ash, depending upon the design of the combustion chamber and the velocity of the gases therein, is carried out of the furnace. This latter fact makes pulverized coal an undesirable fuel for regenerative furnaces employing the ordinary type of brick checker chamber, as the ash causes rapid clogging of the checkers. This feature is not so objectionable in other types of furnaces, for in most cases, notably that of boiler installations, it can be eliminated through proper design, and in some cases can even be turned to an advantage.

Raw Materials: Up to about 1918 only high volatile bituminous coal was considered suitable for either powdering or pulverizing. With improvements in pulverizers, however, the field of raw material was extended, until today not only all types of bituminous coal, but anthracite, coke, lignite and even peat have been successively pulverized and burned. This is another advantage to the credit of the pulverizers, in that it makes available for use some fuels that could not otherwise be used efficiently or economically. But for all-round efficiency, the high volatile bituminous coal, containing from 28 to 35 per cent. volatile matter, remains the best. It is hardly necessary to say that the lower the ash content, and in most cases, the less fusible the ash, the better the coal.

Preparation and Pulverization of the Coal: The development of any promising process always invites the attention of many investigators and inventors, and as a result many plans and devices may be tried before a point of standardization is reached. This statement is particularly true of pulverized fuel. Again, during the course of the development, or when the product may be derived from different sources and be applied to many different purposes under a multiplicity of conditions, as is the case with pulverized fuels, it is difficult to predict which plan and which device will eventually become the standard, or whether any one plan or device can become the standard under all conditions. Obviously the only fair way to treat such a subject is to describe fully and impartially all plans and devices. Needless to say, to pursue such a course in the present instance would require a goodly sized volume in itself. So, in treating of the plans and devices for preparing and utilizing the pulverized fuels, we can do no better than to refer the reader to the published works upon the subject.[1] However, for the convenience of the general reader a very brief discussion covering some of the chief features of preparing, handling and burning pulverized coal is given herewith. The various steps in preparing and utilizing the fuel are as follows:

Crushing the Coal: The first step in preparing pulverized coal is that of crushing, in which the lumps of the run-of-mine coal are broken down to the size required by the pulverizers. This size varies from ⅜

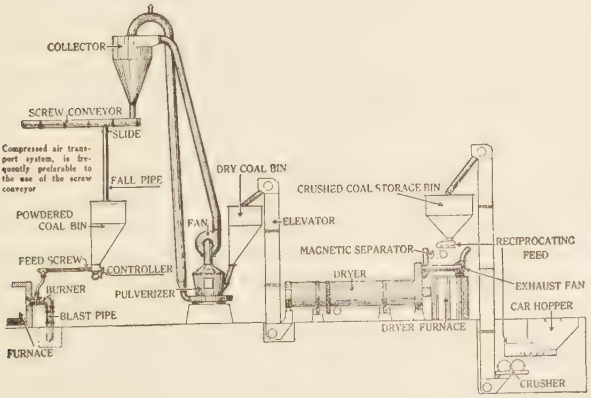


FIG. 16 Diagram of Complete Coal Pulverizing Plant for Indirect Firing. The "Rayco System". (Courtesy Raymond Bros. Impact Pulverizer Co.)

[1] "American Fuels" by R. F. Bacon and W. A. Hamor contains a chapter of 241 pages on Finely Divided Fuels, by F. Parkman Coffin, which treats the subject very thoroughly. This work is published by McGraw Hill Book Co., New York. See also, "The Uses of Powdered Fuel Under Steam Boilers" by Harlow D. Savage, Year Book of The American Iron and Steel Institute, 1921, page 151. "Powdered Coal as a Fuel", by C. F. Herington, Second Edition, 324 pages. Published by D. Van Nostrand Co., New York.

to 1½ inches, major axis dimensions, according to the size and type of pulverizer employed. For this purpose crushers of the single or double roll types are generally employed. These crushers are usually placed below ground level so that the coal may be dumped from cars or trucks into bins and fed to the crushers by gravity. The coal from the crusher or crushers drops either into a small bin or upon a belt that conveys it to such a bin, whence it is elevated by bucket conveyor to the crushed coal bin located at a suitable height, usually 30 to 40 feet, directly above. From this bin the coal may be fed directly into the pulverizers or into dryers as conditions may require.

Drying the Coal: Until recently it was thought necessary to dry the coal, and practically all the pulverizing plants built prior to 1920 were equipped with dryers. Almost without exception these were rotary dryers. While there are different types of these dryers, they all employ the same fundamental principle of operation. The essential part consists of a large steel drum about 30 feet long mounted upon rollers with its axis at an angle of a few degrees to the horizontal so that it may be revolved slowly by a motor driven pinion which meshes with a ring gear encircling the drum. Internally this drum is provided with a number of longitudinal ribs or plates. The crushed coal is introduced at the elevated end of the revolving dryer, and, being lifted by the plates, it passes slowly toward the lower end, being scattered and dropped many times on the way, through a current of hot gases. The drum, in different types, may be heated externally or internally by hot gases from a small furnace or grate. When heated internally the hot gases may be introduced directly into the drum at its lower end, or indirectly through a concentric pipe leading from the furnace located at its elevated end. The dryer discharges the coal through a gas-sealed opening at the lower end into a bucket conveyor that delivers it to the feeder bin above the pulverizer.

Drying Not Always Necessary: The drying was thought necessary to enable the pulverizing machines to operate most efficiently, to prevent the coal powder from packing in storage bins, to decrease the chances of spontaneous combustion, and to obtain the highest temperature and efficiency in burning the dust. Experience has taught, however, that with ordinary air-dried run-of-mine coal and the better designed apparatus, drying is not only unnecessary but may be actually detrimental in some of the operations. In the case of very wet coal or of other raw materials having a high moisture content, a certain amount of drying is still necessary. In all cases the moisture in the fuel should be reduced only to the point where it is in equilibrium with the moisture in the air. In burning pulverized bituminous coals under boilers the heat losses due to moisture in the coal amount to about .1 per cent. for each per cent. of moisture.

Pulverizing the Coal: Many different types of mills operating upon several different principles have been, and are, employed for pulverizing

coal, but recently two types have forged ahead of the others. These are commonly known as the Raymond and the Fuller Mill, both of which are illustrated on the next four pages. In each, the pulverizing elements consist of a stationary manganese steel ring, the "bull ring," and two or more moving parts which roll about its inner circumference, each being driven through a spider mounted at the top of a shaft concentric to the ring, so that the pressure for grinding is imparted wholly or largely by centrifugal force. In the Raymond mill the moving elements are chilled iron rolls, which are mounted on the lower ends of shafts suspended from journals on the ends of the arms of the spider. These internal journals and bearings make it necessary to shut down the mill at regular intervals for lubrication. In the Fuller Mill all necessity for lubrication is avoided by using balls for the moving elements, which are propelled about the ring by means of pushers attached to the arms of the spider. In both cases, the pulverizing elements are enclosed with a gas tight cylindrical steel shell, to prevent the escape of the dust. Both machines are provided with mechanical feeders, whereby the amount of coal entering the pulverizer may be controlled as desired up to the maximum capacity of the machine. Upon dropping into the pulverizer, the crushed coal is thrown against the ring and in the path of the rollers or balls by means of an equal number of plows which are also attached to the spider. Both machines operate at low speeds, from 100 to 200 r. p. m., according to size or capacity and other conditions, and both depend upon air separation for removal of the dust, and largely also, for controlling the fineness, though the Fuller machines may also be built to discharge the dust through screens at very low pressure. As the dust from undried coal clogs the screens, this type cannot be used to pulverize green coal, and requires the installation of a drier.

Separating the Dust: These two machines differ somewhat as to the manner of introducing the air and separating the dust, but the plan employed in the Raymond machine will serve to illustrate the principles of simple air separation. In this mill the separating air is introduced through openings below the pulverizer ring from a spiral pipe that encircles the base of the machine, and is drawn out through a central pipe in the top by means of a fan placed in the line, as shown in Fig. 17. As the air passes upward, it carries the finest dust with it to the fan, which then forces the mixture through another pipe to a cyclone separator. This device has the form of an inverted cone, and is much larger in diameter at the top than the conveyor pipes, of which the exit pipe is concentric with its axis and projects for some distance into the cone. The dust-laden air enters at the top of the separator on a tangent and is, therefore, given a swirling motion downward at the same time that its velocity is reduced; so, the dust, thrown against the wall of the separator by centrifugal force and drawn down by gravity, settles to the bottom of the separator. The air, now carrying but little dust, passes out through the exit pipe and is conducted back to the pulverizer, completing the circuit, which is practically a closed one except for a small vent in the return pipe.

Methods of Conveying the Dust: Owing to the explosive and other peculiar properties of pulverized coal, it can be handled only through a system of pipes and tightly closed bins, or tanks. Therefore, its distribution presents a more or less difficult problem, for while it is highly mobile under certain conditions, it is lacking in hydrostatic properties and will not flow through pipes from its own head. Three general methods are available for its transportation, namely, the screw conveyor, pneumatic conveyor, and tank cars or trucks. The last are applicable only to long-distance transportation and are seldom used, hence will not be further considered here.

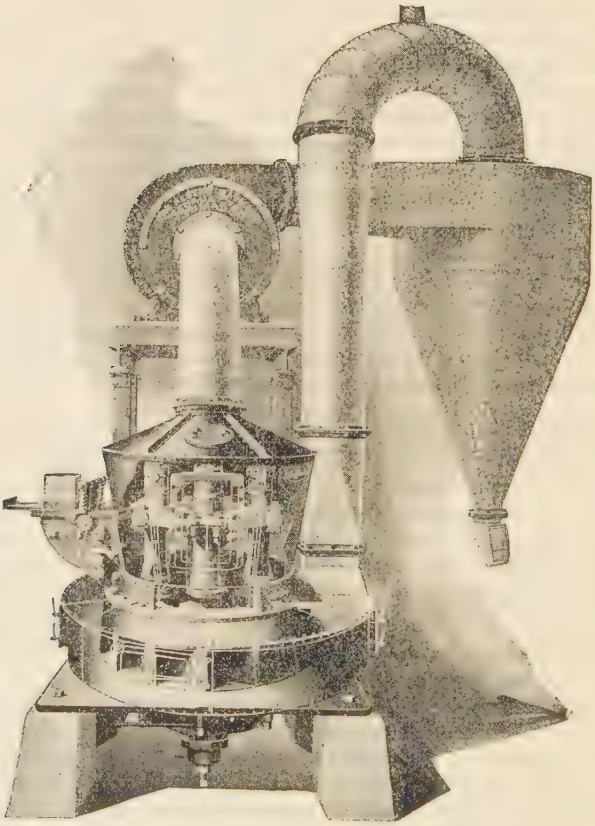


FIG. 17. Skeleton View of Raymond Low Side Four Roller Mill Equipped with Air Separator (bottom), Exhaust Fan (top) and Cyclone Collector (right). For pulverizing dried or undried coal. (Courtesy Raymond Bros. Impact Pulverizer Co.)

The Screw Conveyor is the oldest method in use. By this plan the pulverized material is propelled through a metal trough, or pipe, by means of a long rotating metal spiral. Where a large quantity of the fuel is to be conveyed over a short distance in a straight line and on the level, as in the case of boilers, for example, it is the cheapest and most satisfactory method. Individual sections of screw conveyors are limited to lengths of about 200 feet; each change in direction requires a section of conveyor; and the limiting angle of elevation is about 15°. Therefore, when the coal powder is to be conveyed a considerable distance, or when it is to be elevated to a height relatively great as compared to the horizontal distance, or when the conveyor line must make a number of turns, the pneumatic method is preferable.

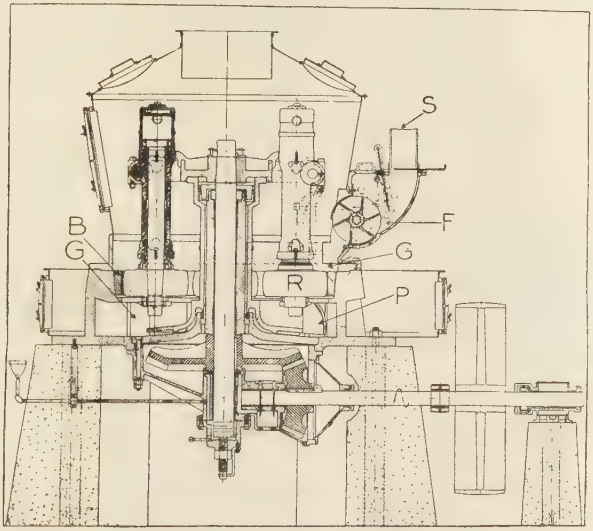


FIG. 18. Cross Section of Raymond Low Side Four Roller Pulverizing Mill for pulverizing dried or undried coal. S.—Spout-intake for Crushed Coal. F.—Automatic Feeding Mechanism. G. G.—Grinding Chamber. P.—Manganese Steel Plows. R.—Pulverizing Rolls. B.—Bull Ring. (Courtesy Raymond Bros. Impact Pulverizer Company.)

Pneumatic Conveying: There are several types of pneumatic conveyor systems. Thus, the coal may be forced through the conveyor pipes by means of compressed air introduced above the coal contained in a specially constructed blowing tank; or it may be aerated, that is, mixed with a little air, to increase its mobility, and then forced along by the air pressure or by columns of compressed air; or it may be mixed with a relatively larger volume of air and carried in suspension to its destination. No data showing the relative merits of these systems under all conditions are available. It is probable that each may have certain advantages over the other under certain conditions. All three methods

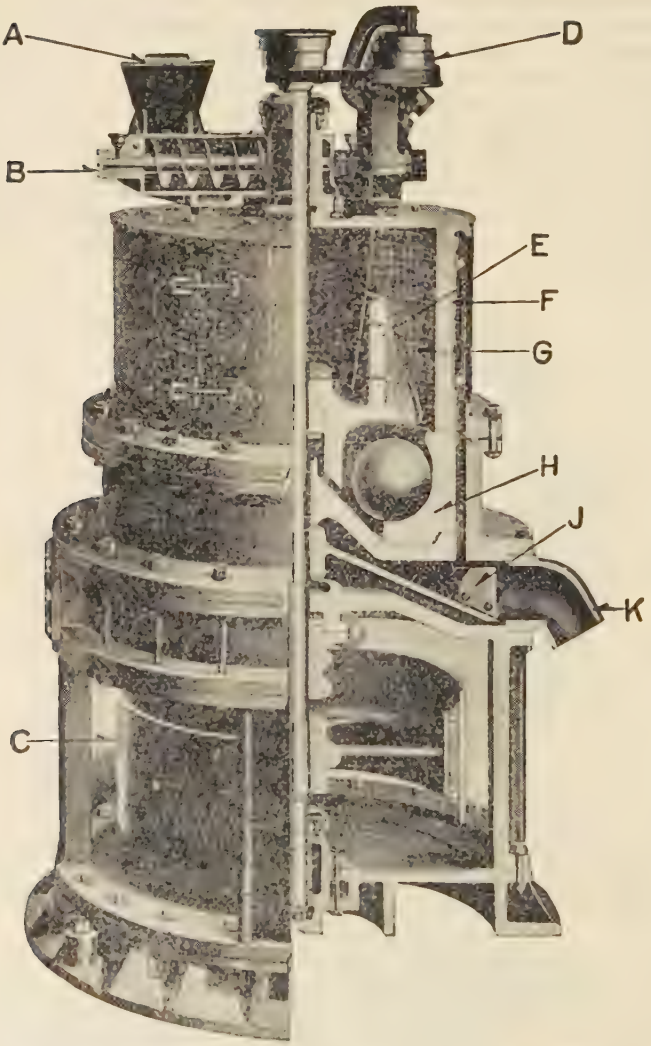


FIG. 19. Fuller-Lehigh Pulverizer Mill. Screen type, pulley driven, for dried coal. A. Feed inlet. B. Feeder. C. Mill driving pulley. D. Feeder drive. E. Separating fan. F. Finishing Screen. G. Protecting screen to F. H. Stationary grinding ring showing one grinding ball in the race. J. Discharge fan. K. Discharge spout for the pulverized coal.

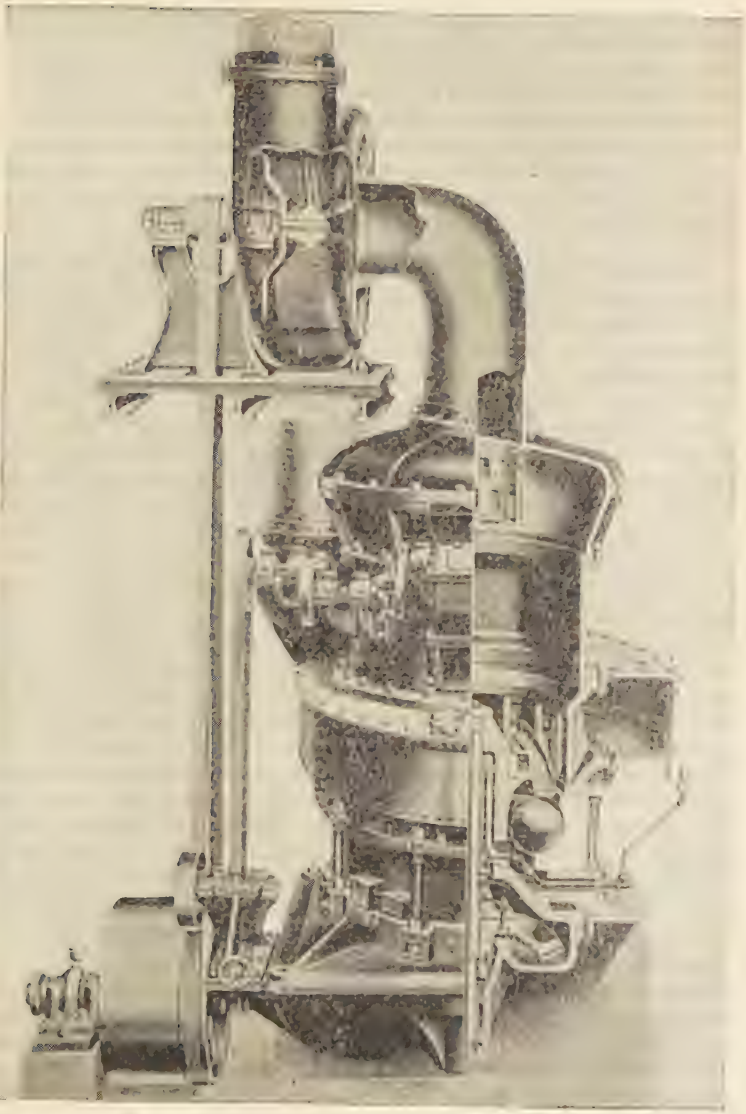


FIG. 20. Fuller-Lehigh Pulverizer. Air Separator Gear Driven Type with Belt Driven Fan, for pulverizing either dried or undried coal.

may be used to convey the powder to bins, but only the third can be used to deliver the coal direct to burners. About 25 per cent. of the air required for complete combustion of the coal, or approximately 50 cu. ft. per pound, may be used in conveying the coal before the mixture will become explosive, but for safety the proportion of air for conveying is kept well below this point. If the coal is not to be carried in suspension, a small fraction of this amount of air is all that may be required. The Fuller-Kinyon system, for example, employs only 10 cu. ft. of air per cu. ft. of coal, which, since a cu. ft. of pulverized coal weighs about 35 pounds, is equivalent to two sevenths of a cu. ft. of air per pound of coal.

Methods of Conveying Dust to Burners: In burning the powder, various plans and many different types of burners and auxiliary apparatus are used, depending upon the method of handling the fuel and the service conditions. Thus, in the preparation and utilization of the fuel, two general systems, which may be termed the unit system and the central-plant-system, may be employed. In the unit system each furnace has its own individual pulverizing equipment, while in the central plant system the pulverizing and separating equipment forms a separate plant which may supply a number of furnaces. In the unit system two general methods of firing may be used, namely, the direct and indirect. In the direct method the coal from the pulverizer is blown directly into the furnace by the pulverizer fan, no separation of dust and air, as just described, being made. This system is applied only in small plants and to furnaces that are fired irregularly or intermittently. In the single unit indirect system the dust is separated as previously described, and the pulverized coal flows by gravity from the separator into a storage bin, from which it is fed to the furnace. This system is applicable to single furnaces that are fired continuously. In the central plant system only indirect firing is possible, but the dust may be collected into a central storage bin, from which it is carried in suspension to the burners of the several furnaces, or be propelled from the separators to individual storage bins located near the combustion chamber of each furnace. From these bins the coal is delivered to the burners by a system of feeders, of which there are two general types, known as pneumatic and mechanical. The first type employs the principle of the pneumatic siphon, and the pulverized fuel is drawn from a fuel box in the base of the bin and delivered to the burner by suction. This siphon may be employed as a separate piece of apparatus, or it may constitute a part of the burner itself. With this type, it is difficult, due to the tendency of the coal powder to pack in the bin, to maintain a uniform flow of the fuel to the burner; and it is still more difficult to control the rate of feed closely, especially when it is desired to feed the coal at a low rate. However, on some feeders of this type these difficulties are said to have been overcome. For these reasons many prefer the mechanical feeders, especially on boilers and furnaces working under variable loads. In these feeders various devices may be used to conduct the coal from the bin, but the short screw conveyor is the one most generally used. This device

is positive in its action, and the rate of feed can be nicely adjusted almost as desired by varying the speed. These devices deliver the coal either directly into the burner, or into a primary air line through which it is blown in suspension to the burner.

Burning Pulverized Coal: As is to be expected from the preceding description, there are many different burners on the market. These vary in principle and design according to the type of feed employed, the kind of furnace in which they are to be used, and the individual ideas of the inventors. The following outline gives a method for classifying these burners, and indicates the possible types, most of which may be found in use:

I. Burners Supplying All Air for Combustion.
- A. Fuel fed direct to burner.
  1. Single air supply under low pressure.
  2. High pressure primary air mixed with fuel; Secondary air at low pressure. Both mechanical.
  3. Primary air, at low pressure, mixed with fuel. Secondary air induced.
- B. Fuel delivered to burner in suspension with primary air.
  1. Secondary air supplied through burner at low pressure either cold or preheated.
  2. Secondary air induced.
  3. Secondary air preheated and supplied under pressure, with provision for inducing cold air.

II. Burners Suppling Part of Air for Combustion, remainder being supplied by the draft — either cold or preheated from coolers, checkers or recuperators.
- A. Fuel fed direct to burner.
  1. Primary air at high pressure used as an injector to draw dust from bin. No secondary air.
  2. High pressure primary air mixed with fuel. Secondary air at low pressure or induced.
  3. Primary air mixed with fuel. No secondary air through burner.
- B. Fuel delivered to burner in suspension with primary air.
  1. No secondary air through burner.
  2. Low pressure secondary air.
  3. Secondary air induced.

In the burners making use of two or more sources of air supply or of two streams of air from one supply, the air designated as primary air is used to aerate the coal, while the secondary air is intended to supply all or a part of the remainder required for combustion and is not mixed so thoroughly with the coal as the primary air. As may be seen from the accompanying cuts, pulverized coal burners vary a great deal in construction and shape, according to the ideas of the inventors and the conditions of service. For the most rapid combustion, the burner should spread the primary air stream over a wide area. Therefore, burners with flat

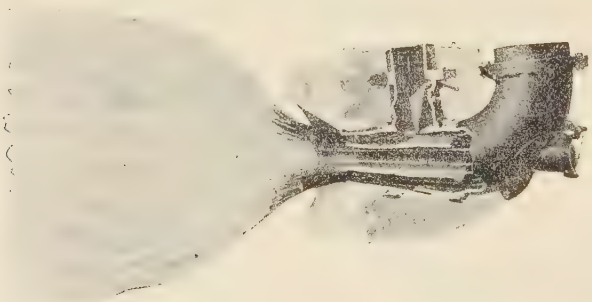


FIG. 21. The "Rayco" Double-tube Burner. This burner is the leading example of the single air supply low pressure type. The fuel is fed through the vertical tube by means of a short screw conveyor. (See Fig. 16.) (Courtesy Raymond Bros. Impact Pulverizer Co.)

or oval exits or burners that provide for a central core of secondary air will give a shorter flame than those in which the coal-bearing stream is confined to the center of a cylindrical column of the air-coal mixture. In burners of this type on high temperature furnaces the coal particles are likely to become fused together, in which case combustion is retarded or incomplete and the flame is lengthened. The pressure at which the air is fed to the burner also affects the length of the flame, a high pressure driving the coal farther into the combustion chamber than a lower pressure. The kindling temperature of pulverized coal is several hundred degrees higher than for gases, and the combustion temperature is also much higher; also, the rate of combustion is slower, and a greater excess of air is required. Consequently, combustion chambers for powdered coal must be more refractory and have a larger volume than for gases, and the draft should be less for highest efficiency. Theoretically, slightly more than 150 cubic feet of atmospheric air is required for the complete combustion of one pound of coal, but in practice additional air to the extent of 20 to 30 per cent. of this amount is required. This fact, together with the absence of carbon in the ash, will explain the high efficiency obtained with pulverized coal as compared to the older methods of firing, for when coal is burned on a grate almost 100 per cent. excess air is required.

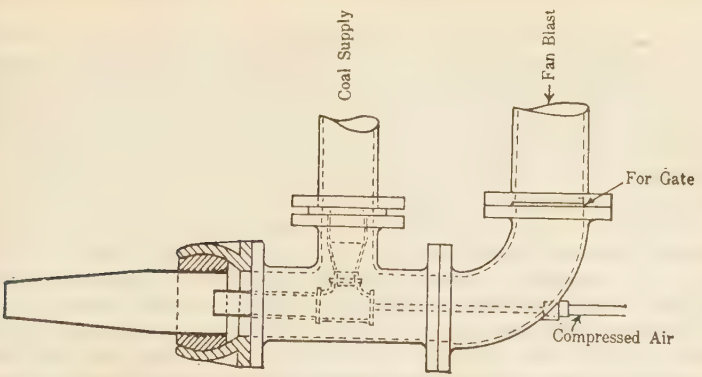


FIG. 22. Coal Burner Used with Mechanical Feed, Double or Triple Air Supply.

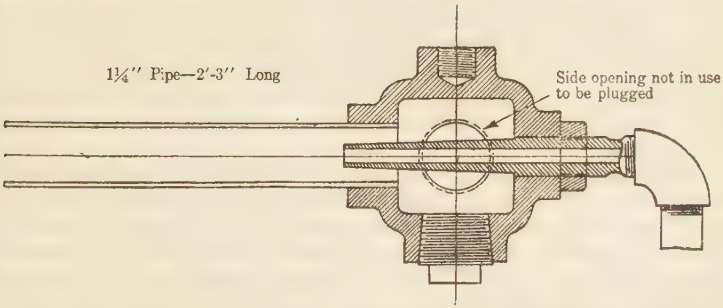


FIG. 23. Coal Burner Used with Pneumatic Feed. High Pressure Siphon Air through Burner, Balance of Air from Checkers. Coal is drawn into burner through one of the side openings.

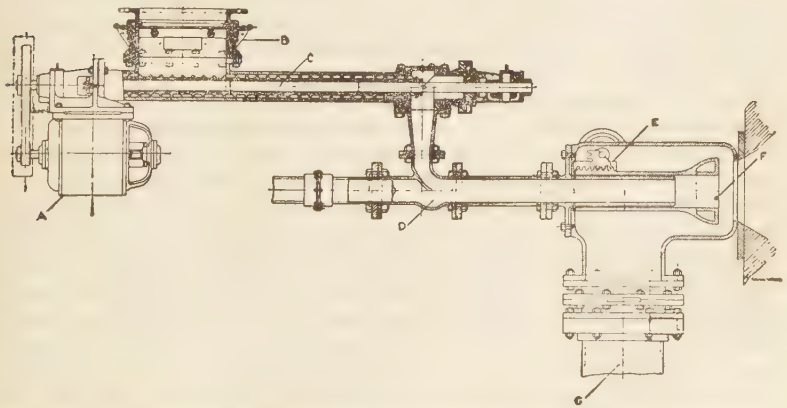


FIG. 24. The Fitch Burner (right) with Feeder (upper left). Double air supply low pressure type. A. Motor for Driving Screw. B. Hopper Gate. C. Screw for Conveying Coal. D. Mixing Tee for Preventing Back Pressure. E. Rack and Pinion. F. Valve to Regulate Secondary Air. G. Secondary Air Inlet. (Courtesy Fuller-Lehigh Company.)

Coke. Coke is the residue that remains after certain bituminous coals have been subjected to destructive distillation. Owing to its peculiar structure and physical, or mechanical, properties, it has become the chief metallurgical fuel. All coke possesses a cellular structure, but there is a wide variation in the degree of porosity for different cokes. Likewise the hardness, brittleness and strength of coke are subject to wide variations. Coke for blast furnace consumption should be free from dust, and the pieces should not be too large to admit of ready combustion, and it must at all times be sufficiently strong to resist pressure, due to the heavy burden, without crushing. In chemical composition, the different cokes show a similar wide variation, though for metallurgical purposes the fixed carbon, which is the only constituent sought, will constitute 85 to 90 per cent. of the coke. The other constituents, roughly stated as ash, sulphur and phosphorus, are impurities. The per cent. of phosphorus in the coke determines whether the coke is suitable for making Bessemer or basic iron. For the former grade, modern practice requires that the phosphorus content of the coke must not exceed .018 per cent. The sulphur content ranges from .60 per cent. to 1.50 per cent., though it is evident that both the sulphur and ash should be kept as low as possible.

Methods of Manufacturing Coke: There are two methods for the manufacture of metallurgical coke, known as the beehive and the by-product, or retort, process. In the beehive process, air is admitted to the coking chamber for the purpose of burning therein all of the volatile products of the coal to generate heat for further distillation. Incidentally, some of the fixed carbon of the coal is also consumed. In the other method, the coking chambers are air tight, and the necessary heat for distillation is supplied from external combustion of the volatile products of the coal; and with modern ovens, properly operated, only about half of the gaseous matter from the coal is used in carrying on the coking process. While the beehive process was, until recently, the leadng method for the manufacture of coke, it is fast being replaced by the by-product process. The processes of manufacture have very little effect on the quality of the coke, but if there is any difference, the latter process has the advantage. There is, however, a difference in appearance, due mainly to the difference in the coking temperature of the two processes, that of the by-product being much lower than the beehive. In general, beehive coke is silvery gray in appearance, while by-product coke is of a much darker color. As examples of these two methods of coking, the following brief descriptions of plants are to be taken as typical of the best modern practice for each process.

SECTION VII.

THE BEEHIVE PROCESS FOR THE MANUFACTURE OF COKE.

The Continental No. 1 Plant of the H. C. Frick Coke Company may be cited as an example of beehive coke practice. It is located near Uniontown, Pa., in the southeastern part of the famous Connellsville coke region. It consists of a coal mine and a coking plant of 400 beehive ovens.

The Mine: Since the coal bed here lies about 330 feet below the surface, the coal is mined through a shaft. Although some gas is given off as the coal is mined, it is prevented from collecting and thus becoming dangerous by a very efficient system of ventilation, which permits the installation of electrical appliances for lighting and the use of both pick and machine methods of mining. The coal seam in this mine varies from seven to nine feet in thickness, but in mining the coal, about four inches at the bottom and from four to eight inches at the top, being high in ash, sulphur and phosphorus, is allowed to remain in order to improve the quality of the coke. Incidentally, this top discard also helps to support the gob, an easily dislodged and treacherous slate-like formation lying between the coal and the hard overlying rock deposit and forming the roof of the mine. The average output of the mine is twelve hundred net tons per day. For transporting this coal through the mine underground, a combination system of electric and rope haulage is employed from certain points, while horses are used to distribute empty cars to and assemble loaded cars from the various working places. From these assembling points the loaded cars are moved by electric locomotives in trains of thirty cars each to a substation, where they are attached to the rope haulage which pulls them to the foot of the shaft. Here they are hoisted, one at a time, to the tipple and automatically dumped into bins. From these bins the coal is loaded by chutes into electric larries which convey it to the ovens some hundred yards away. Each larry holds sufficient coal to charge one oven, and it will be noted that run-of-mine coal is used for coking, no crushing nor preparation of any kind being necessary.

Construction and Arrangement of the Ovens: As to the essential features of construction, the name beehive is literally descriptive of the form of the bechive oven. The dome-like chamber, built on a suitable foundation, is constructed of highly refractory brick, has a flat but slightly sloping bottom, an opening in the top, the "trunnel head," through which the coal is charged and the products of distillation and combustion escape, and an arched opening at the bottom, called the door, through which air is admitted for combustion and the coke is watered and drawn. In general, the dimensions of different ovens vary a great deal. The ovens at this plant are each 12 feet 3 inches in diameter and 8 feet high from the bottom to the top of the dome, inside dimensions. Of this height, the side wall, built of fire brick, rises vertically a distance of 27 inches, and is capped

by the crown which is built of silica brick. Except in the case of the special brick used about the openings, the brick in these walls are of standard size and are laid ends in and out, thus making both the side wall and the crown wall approximately 9 inches thick. Finally, this brick structure is covered on the outside and up to the level of the "trunnel head," which is 14 inches in diameter, with loam or rough clay which acts as an insulator of and a store house for heat. For retaining this loam covering, there are in general three different arrangements of ovens as follows: (1) the bank system, in which the ovens are built in single rows against a bank of earth, natural or artificial, thus making it necessary to build but one retaining wall along the front of the ovens; (2) the single block system, which consists of a single row of ovens with retaining walls at both the front and back; and (3) the double block system, in which the ovens, in a double row, are built back to back or staggered with a retaining wall extending along the front of each row. At this plant there are four double block batteries and two batteries of banked ovens.

Waste Heat System: One battery of the banked ovens, forty in number, is arranged for utilizing the waste heat from the products of combustion to generate steam. For this purpose a large tunnel is constructed in the bank some 10 feet back of the ovens and parallel to the battery. This tunnel is connected to each oven by means of a small flue, which conducts the hot gases out of the oven from an opening sufficiently above the side wall to prevent its being closed by the largest charge of coal used. Each flue is provided with a damper for closing off the draft during the period the oven is being watered, drawn and charged. From the battery, the tunnel passes to the boiler house, where branches conduct the hot gases through the fire boxes and flues of the boilers which are connected to a common stack, about 100 feet in height to cause the proper draft. During the coking period, the "trunnel head" is necessarily kept tightly closed. Owing to the increased draft, these ovens are inclined to run up a little higher temperature than the ordinary oven, so that the temperature in the tunnel is high, sometimes reaching 1500°C. A maximum of about 800 horsepower is generated from the waste heat from this battery of forty ovens.

Charging the Ovens: The ovens are charged as soon as practicable after drawing, so that the stored up heat from the previous charge will be sufficient to start the coking process. In the case of new work, the ovens must be heated up gradually to a coking temperature by means of wood and coal fires, after which period small charges of coal for coking are used until the ovens reach normal working conditions. With the oven in readiness for charging, the door is bricked up to within about one and one half inches of the top; and the charge, which consists of six and one half tons of coal for 48-hour coke and eight tons for 72-hour coke, the latter being made over the week-ends, is dropped through the "trunnel head" from the larry above, leaving the coal in a cone shaped pile in the oven. In

order to secure uniformity in the coking of the coal, this pile must be leveled so that the coal will lie in a bed of uniform depth over the entire bottom of the oven. This result is attained by means of an electrically operated leveling machine, which is moved from oven to oven on the same tracks that the charging larry uses. The essential part of this machine consists of a vertical rod and sleeve, on the lower end, or head, of which is mounted two collapsible leveling arms. By means of suitable gear connections with an electric motor, this apparatus, with the head closed, may be mechanically lowered through the "trunnel head" upon the apex of the pile of coal, when the rod and sleeve are made to revolve and the leveling arms are at the same time slowly extended. These motions, combined with the continued lowering of the head, distribute the coal to a uniform depth in a very few minutes. In works not equipped with this machine, the leveling is accomplished by means of a large long-handled scraper, operated, by a laborer, through the door of the oven, which is purposely bricked up to about only two-thirds of its height at the time of charging.

The Coking Process begins very soon after the leveling is completed, as the ovens retain enough heat in the brick of the walls and the loam backing to start the distillation of the volatile matter of the coal. As more and more heat is conducted through the walls from the hot loam backing, the temperature of the interior of the oven soon reaches the kindling point for these volatile gases, which, in the presence of the air admitted to the oven, ignite with a slight explosion at first, then continue to burn quietly in the crown of the oven, or, as small candle-like flames at the surface of the coking mass, thus supplying heat to continue the process. The coking proceeds from the top of the coal downward, so that the coking time depends mainly upon the depth of the coal. The volume of volatile matter thus rapidly approaches a maximum, which is maintained for a period, then declines to practically nothing, hence the burning of this volatile matter must be regulated by gradually closing up the opening at the top of the door for the admission of air. This regulation is very necessary to maintain the temperature at a maximum, and conserve coke, as an excess of air at the beginning of the coking period tends to cool the oven, and later consumes the carbon of the coke. The yield is also reduced by improper leveling. If the coal is not of uniform depth to begin with, the thin portions coke through before the thick, and some of the coke in the thin sections is consumed while the coking of the thick portions is being completed. On the other hand, if the process be stopped when the thin areas have coked through, there will be a loss due to green butts on the thick areas. It will be recalled that the coal assumes a semifused, or pasty, state during the coking process. The result to be expected from such behavior is that the coke would be found in a continuous mass, or cake, at the end of the process; but, due to expansions and contractions of the mass in coking and on cooling, the cake is ramified by a great number of irregular vertical

fissures, thus giving it a long columnar structure, in which the very irregular columns extend from the top to the bottom of the cake. This structure affords a second means by which beehive coke can be distinguished from by-product.

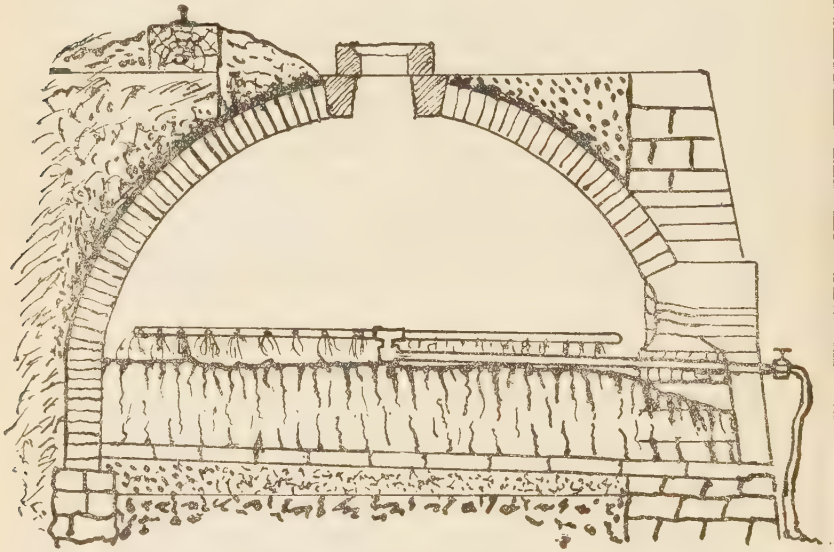


Fig. 25. Ideal Section of Beehive Coke Oven Showing Watering Machine in Use and Structure of Coke.

Watering and Drawing the Coke: As soon as the volatile matter has ceased to be evolved, as indicated by a subsidence of the smoke at the "trunnel head" and a decided shortening of the candle flames on the surface of the coke, the coke should be drawn. In good practice, the charge will be so regulated that this point is reached near the coking time assigned, and the ovens will be drawn on a schedule. If any circumstances delay the drawing, the doors of the ovens are sealed tight with clay, and the draft at the "trunnel head" is reduced. However, it is very important that the ovens be drawn on schedule, as a delay results in burning some coke and in cooling the oven, so that it will not coke the next charge in the period assigned. At the end of the coking time, then, the brick work closing the door is torn out, and the coke is watered out. At Continental this watering is accomplished by a self propelled spraying device. It consists of a tube or pipe a few inches shorter than the diameter of the oven, pivoted at the center to a feed pipe and perforated by two rows of holes on opposite sides, starting from the center. The holes are arranged to throw jets of water horizontally, which causes the pipe to revolve. Where this device is not

provided, the ovens are watered by spraying with a pipe on the end of a hose in the hands of a laborer, who directs a stream of water through the door of the oven. For drawing the coke, a Covington coke drawing machine is employed at this plant. It is provided with a long arm fitted with a head, flat on the bottom, but inclined on the top, and a pair of hinged ears, or drawing lugs. Upon being pushed by motor into the oven, the head moves in advance of the drawing lugs, which lie flat, and raises the coke from the bottom of the oven. Upon the return, the lugs engage this loosened coke and force it through the door in advance of the head. Here the coke falls upon a belt conveyor running parallel to the ovens, and is carried to the loading conveyor, which is inclined and extends at right angles to the row of ovens. At the top of the loading conveyor the coke falls upon a stationary screen, to separate the breeze, then slides down a chute into a railroad car, and is ready for shipment. It is impossible to remove all the coke with the machine, and what remains must be drawn by hand, so while the machine moves forward to the next oven, a laborer cleans out the oven with a long handled scraper, drawing the coke out upon the conveyor of the machine, which is more than long enough to span the distance between the doors of two adjacent ovens. In straight hand drawing, the coke is drawn out into the yard and forked into barrows, which are used to wheel the coke into railroad cars.

Longitudinal Ovens: In order to adapt better the beehive oven to the use of mechanical devices and effect a saving in labor, there appeared in 1906 a modified form of the old Belgian oven, known as the Mitchell oven. The essential features of this type of oven are a long narrow chamber, rectangular in shape, with a flat tile bottom, an arched roof sloping towards the ends, a "trunnel head" in the center of the roof, and two doors, one at each end, which extend over the entire width and height of the oven ends. These ovens are built side by side in blocks or batteries, and are charged, controlled and watered like beehive ovens. The coke is pushed out of the oven by a mechanical pusher upon a loading conveyor which is made to screen the coke and drop it directly into railroad cars.

SECTION VIII.

THE BY-PRODUCT PROCESS FOR MANUFACTURING COKE.

General Features of the Process: The by-product process, being a true distillation process, involves the use of retort ovens. While there are many modifications, these ovens may be said to consist essentially of three main parts, namely, the coking chambers, the heating chambers, and the regenerative chambers—all constructed of brick. The retorts are rectangular in section, varying in general from 30 to 42 feet in length, from 6 to 13 feet in height, and from 12 to 22 inches in width, and are built in batteries, of from 10 to 90 ovens, in which the coking chambers alternate with the heating chambers. The coal is charged through openings in the top of the oven, and the coke is pushed out one end by means of a power driven ram, or pusher, acting through the other end. All quenching, or

watering, of hot coke is done outside of the oven. During the coking period, the ends of the oven are closed by brick lined doors, while an opening in the top, connected with suitable pipes, provides a means for the escape of the volatile products of the coal, which must undergo several different treatments in order to separate the many valuable products. As to the combustion chambers, these consist of a great number of flues, in order to secure a uniform temperature throughout the entire length of the oven, and may be either of the horizontal flue or of the vertical flue type. While some of the older ovens employed the recuperative principle for pre-heating the air for combustion, modern practice demands the use of regenerative chambers, because the heat is better conserved and less gas is required thereby to operate the oven. In the arrangement of these regenerators, two plans have been employed with about equally good results. By the first plan the regenerative chambers, two in number, are placed longitudinally beneath a whole battery of ovens, but in the second plan a regenerator is placed under each end of each oven. The latter has been employed in the most up-to-date plants, because each oven is thus made more nearly an independent unit, and the operation of the whole battery is not liable to be influenced by one or two ovens that may be shut down for repairs or other reasons.

Advantages of the By-product Process: From the brief description given above, it will be surmised that the initial cost of a by-product installation is very great. Nevertheless, owing to its many advantages, the method is rapidly becoming the leading process for the production of coke in this country. These advantages, as stated by Mr. Carl A. Meissner, are as follows:

1. "It is practicable to ship to it (the by-product plant) coking coals from any section within a radius of a favorable freight rate.
2. Many coals not suitable for coking in beehive ovens become available for by-product ovens by mixing with other coals and are so used to make a first-class blast furnace coke.
3. Coking coals in by-product ovens permit of the full recovery and use of the very valuable by-products and the gas.
4. The cost of making by-product coke at the iron and steel works is considerably less than the cost of making beehive coke at the coal mines and transporting the coke to blast furnaces, especially when located some distance away from the beehive district.
5. The profits thus obtained give a substantial return on the investment in by-product coke plants, large though such investment may at first appear."

The Plant of the Clairton By-product Coke Company is located at Clairton, Pa., in close proximity to the Clairton Steel Works and Furnaces. This plant is the largest of its kind in the world. It consists

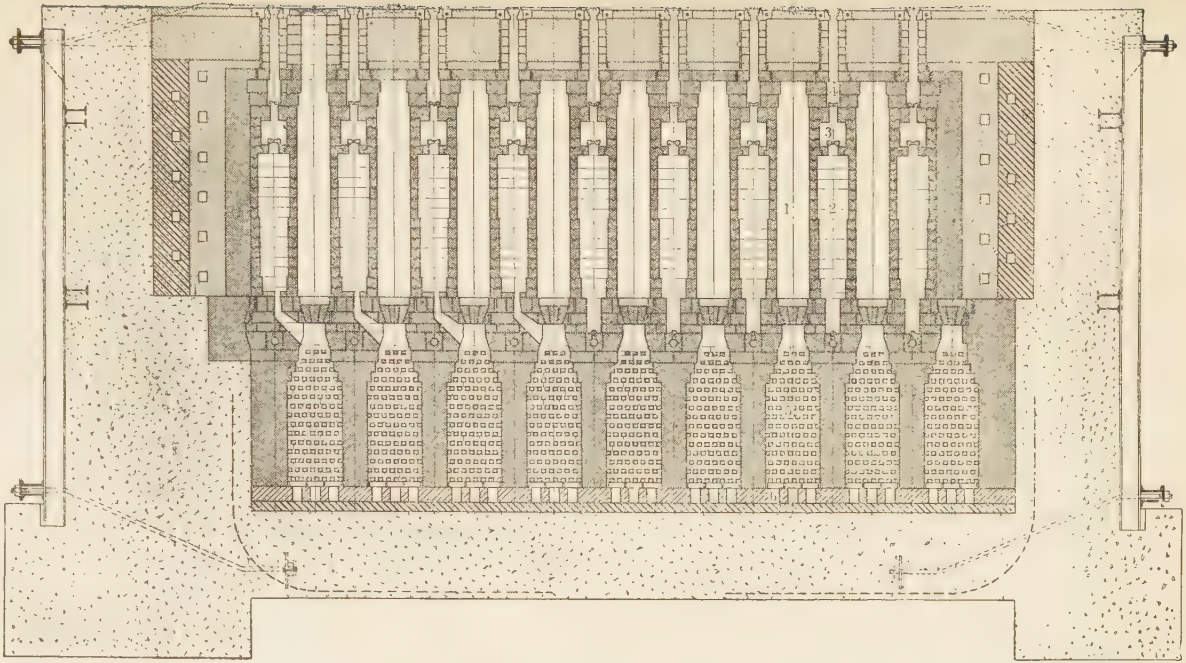


FIG. 26. Koppers By-Product Coke Ovens.
Illustrating Cross Section of Battery.
1. Coking Chamber. 2. Heating Chamber. 3. Horizontal Flue. 4. Opening to Top. 5. Regenerative Chambers.

of two units, some ovens of the first of which were operating in the Spring of 1918, while a section of the second unit was put in operation in the Spring of 1924. The ovens are constructed in batteries of 64 ovens each in the first unit and 61 ovens each in the second. These batteries are arranged in parallel rows of 6 batteries each, and the older unit is made up of two of these rows with the coke, or delivery, sides facing each other. Each oven of the first unit has a capacity of 13.2 net tons of coal per charge, while the capacity of the ovens in the completed part of the newer unit is 16 net tons per charge. The usual operating schedule for the older unit is 19 hours, while the coking time of the newer ovens is 17 hours. On these schedules, the 1134 ovens now in operation, are capable of coking more than 20,000 net tons of coal per day. From this coal there are produced in the neighborhood of 14,000 net tons of furnace coke; 1,300 net tons of breeze and dust, which is used to generate steam for the plant; 231,000,000 cubic feet of gas (average thermal value 590 B. t. u.), 64 per cent. of which is surplus not needed for heating the coke ovens at the plant and therefore available as fuel gas for the mills; 239,000 gallons of tar; 546,000 pounds of ammonium sulphate; 57,100 gallons of motor benzol, or 42,000 gallons C. P. benzol, 9,660 gallons C. P. toluol and 8,800 gallons refined solvent naphthas; and 8,800 pounds of crude naphthalene. The coal for the works is obtained from the mines of the H. C. Frick Coke Company in the lower Connellsville Field, and is known commercially as Klondike coal. These mines are located near the Monongahela River, and the coal is transported from the mines to the coke works by water, for which purpose 255 barges of 1,000 net tons capacity each and 9 steamers are employed.

Construction of Older Ovens: The ovens of the first unit are known as the Koppers 500-cubic-foot by-product oven. All parts of these ovens are constructed almost entirely of the best grade of silica brick. To give the coking chamber a volume of 500 cubic feet, each oven inside has a length of 37 feet from face to face of the doors, a height of 9 feet 10 inches from floor to roof, and a width that tapers from 17 inches at the pusher end to 19½ inches at the discharge end. Four charging holes in the top provide means for admitting the charge, while a separate opening at one end provides an outlet for volatile matter. The oven is of the vertical flue type with individual regenerative chambers. The heating chamber is composed of a total of thirty vertical flues, which rise from the bottom of the chamber, where they are provided with openings to the regenerative chambers and to the gas mains, to a large horizontal cross-over flue on a level a little below the top of the coking chamber. A dividing wall near the middle of the oven separates this chamber, except the cross-over flue, into two parts with sixteen vertical flues on the narrower end of the oven and fourteen on the wider end. Each end, approximately each half, of the oven may thus be heated alternately, and in practice the reversals are made, automatically every half hour for each battery of sixty-four ovens, by means of a reversing motor controlled by an electrical clock attachment. Two large underground flues,

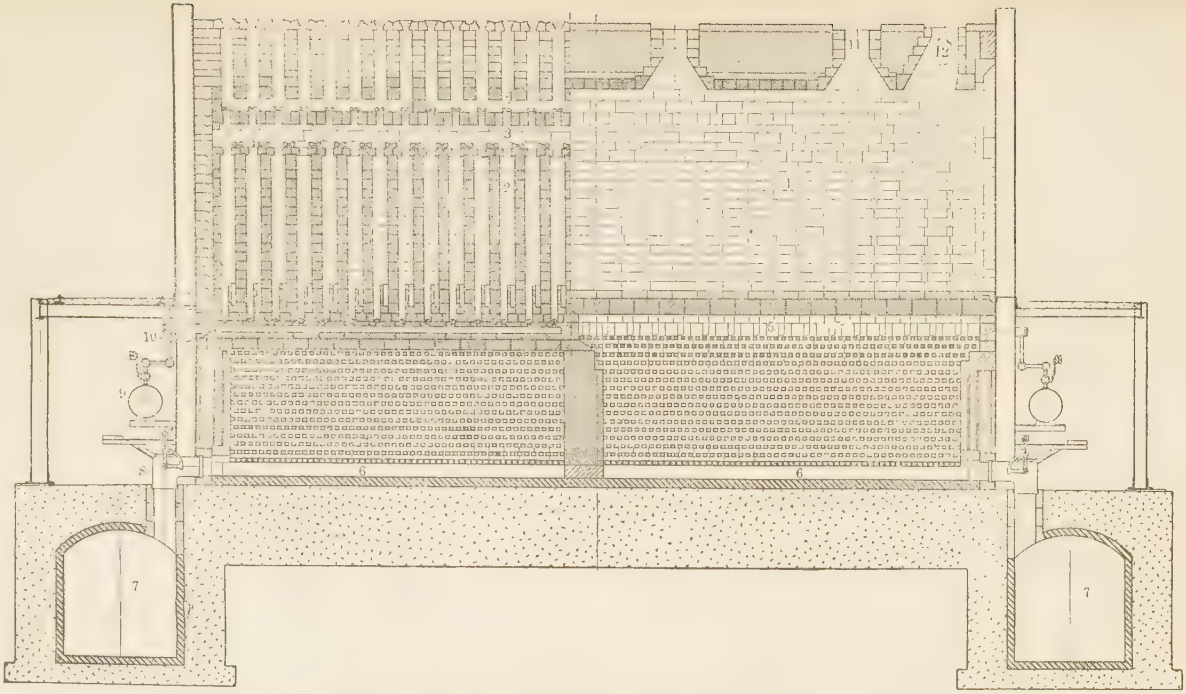


Fig. 27. Koppers Standard Coke Oven. Longitudinal Section of Coking and Combustion Chambers.
1. Coking Chamber. 2. Combustion Flue with gas nozzle at bottom. 3. Horizontal Flue. 4. Opening through top.
5. Checker Chamber and Flue. 6. Flues under checkers. 7. Flue to stack. 8. Cast iron connection from checkers to stack flue.
9. Gas main. 10. Gun brick. 11. Charging Hole. 12. Outlet for Volatile Matter.

one on each side, extending along in front of and parallel to the battery and connected to the checker chambers by means of cast iron goose necks, furnish means for the escape of the products of combustion. These flues lead to a stack, which is located at one end of the battery and is 200 feet high, in order to furnish the draft necessary to draw the gases through their tortuous course. An idea of the magnitude of the structure may be gained from the fact that a single battery of these ovens contains the equivalent of about 2,500,000 nine-inch brick.

Method of Heating Koppers Ovens: This construction may be further explained by tracing the course of the gases when the ovens are in operation. The air for combustion is admitted to the checker chamber through a capped opening on the goose neck leading to the stack flue. From the top of the regenerators it is delivered through individual openings into each of the fourteen or sixteen vertical flues on the side of the oven where the combustion is to occur. Likewise, the gas for combustion, which is conducted from the gas main into a fire brick gas duct located below the vertical flues, is admitted through individual fire brick nozzles to each of the vertical flues, about 10 inches below the air openings. Thus, the gas and air meet in the flues, combustion occurs, and the hot waste gases are carried over to the opposite side of the battery by the horizontal flues, then down the vertical flues, through the checker work, out through the goose neck and into the large flue that leads to the stack. In order to secure uniform heating of the oven at all times, individual regulation of the draft in each vertical flue is provided by means of a brick that may be pushed out over the top of the flue to reduce the size of the opening. In the top of the oven an opening, which is closed by a plug except as occasion demands it to be opened, provides access to the sliding brick and also to the gas nozzle in case it is desired to change the amount of gas admitted. The total amount of air admitted to each oven is controlled by an adjustable valve at an opening in the goose neck.

Construction of New Ovens: The ovens of the second unit are of a type known as the Becker oven. With respect to the form and general arrangement of the coking and heating chambers, these ovens are similar to the Koppers ovens, their prototype; but the heating chambers are provided with a radically different system of cross-over flues, which were designed to make it possible to employ a somewhat different plan for heating the coking chambers. Thus, instead of having the horizontal flues extend from one side of the battery to the other, or from end to end of the combustion chambers, they are each about equally divided into two or four flues, and these short flues are connected to similar flues on the opposite side of the oven by means of four or six (six in the newest models) short cross-over flues extending over the top of the coking chamber as shown in Fig. 28. Therefore, instead of firing the two sides of a battery, or the ends of the ovens, in alternation, a side of each oven in a battery

is fired in alternation with its opposite side. This plan makes possible a better control over oven temperatures and provides for a better distribution of the heat in the coking chamber, which is necessary in order to coke all the coal in a charge in an allotted time. The plan, of course, involves certain changes in the reversing equipment, to provide for the

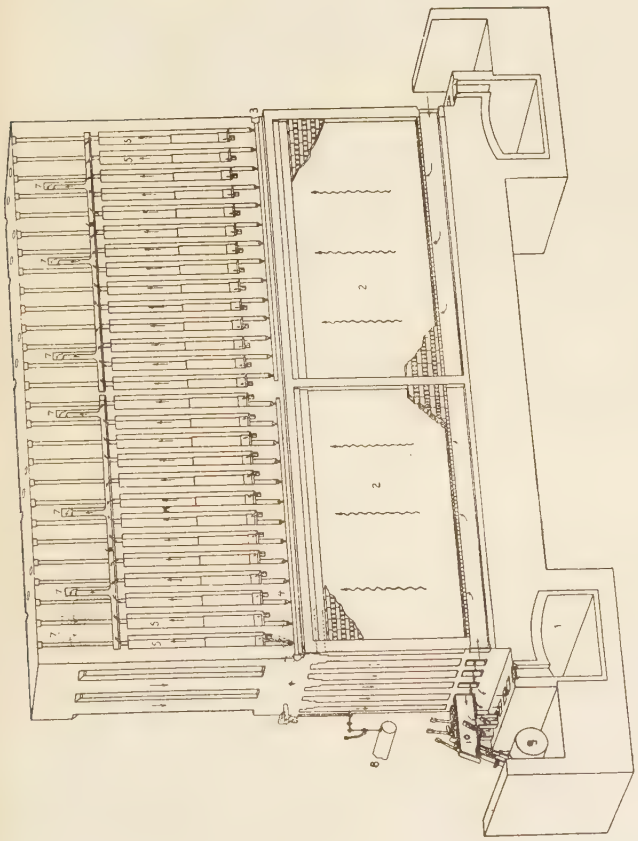


FIG. 28. Skeleton Drawing of Becker Oven. 1. Flue to stack. 2. Checker chamber. 3. Gas duct for coke oven gas. 4. Gas nozzles. 5. Vertical combustion flues. 6. Horizontal flues. 7. Cross-over flues. 8. Main for coke oven gas. 9. Main for producer gas. 10. Gas and air connection to stack flue, showing arrangement of valves. (NOTE: Clairton ovens have 4 cross-over flues instead of 6.)

intake of air for combustion and for the egress of the products of combustion. Since the products of combustion must pass out through both stack flues at the same time, each checker chamber is provided with an individual valve for closing its connection to this flue while being used to preheat the air. Each of these valves is connected to a single shaft which also controls the air valves, and all these valves in a battery, together with the gas valves, are opened and closed automatically by a reversing motor located at one end of the battery and controlled by an

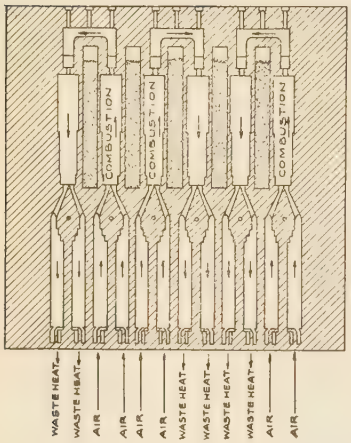


FIG. 29. Flow Diagram of Battery of Becker Ovens. Illustrating flow of gases when ovens are fired with coke oven gas.

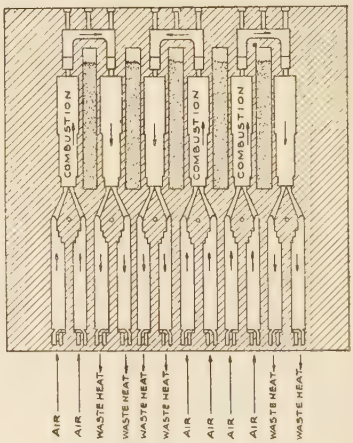


FIG. 30. Illustrating flow of gases when ovens are fired with gas and air reversed, as compared with Fig. 29.

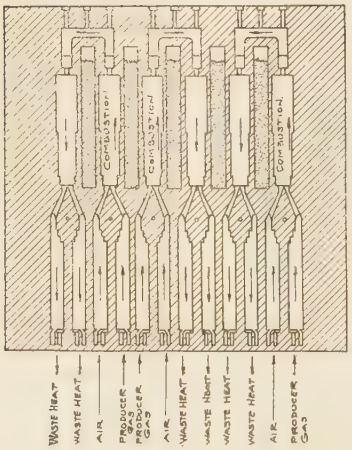


FIG. 31. Flow Diagram of Battery of Becker Ovens. Illustrating flow of gases when ovens are fired with producer gas.

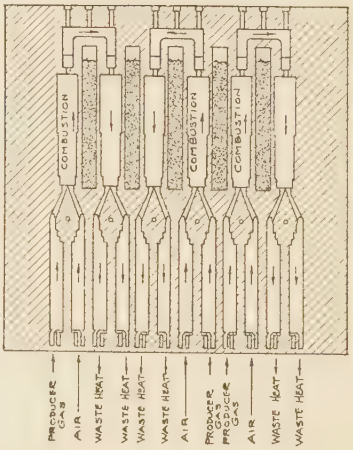


FIG. 32. Illustrating flow of gases when ovens are fired with gas and air reversed, as compared with Fig. 31.

electrical clock attachment. To adapt the ovens to producer gas or a combination of fuels, each checker chamber is divided longitudinally, by a solid brick wall, into two equal-sized compartments, and these are paired with the two similar compartments of an adjacent checker chamber as shown in Figs. 29 to 32. When the ovens are operating on oven-gas exclusively, both these chambers are used to preheat the air. Since the outer side of the oven at each end of a battery must be provided with a combustion chamber, and the cross-flues are built over every other coking chamber, each battery must contain an odd number of ovens.

The Other Important Changes in the ovens relate mainly to the dimensions. The Becker oven is narrower than the Koppers oven, being 16 inches wide at the pusher end and 18 inches wide at the coke end. To secure the increased capacity, the newer oven is, therefore, somewhat higher and longer than the old oven. Inside, the coking chamber has a height of 11 feet 8½ inches, while the length, from face to face of the doors, is 40 feet. The outside length of the ovens from face to face of the brick work is 42 feet, 9 inches. These dimensions give the coking chamber a coking volume of 612 cubic feet. The decrease in the width reduces the coking time by about one hour, so that any further gain in the coking time is to be attributed to the greater efficiency of the new type of cross-over flue.

Drying and Heating New Ovens: Great care is required in preparing new ovens for their first charge. This preparation is carried out in two stages, namely, a drying and a heating period, in both of which the temperature of the ovens must be raised very slowly and uniformly, in order to avoid uneven expansion and consequent cracking of the brick work. Both operations are carried out by building fires in the coking chambers, which are temporarily provided at each end and near the tops with a number of small holes, less than two inches in diameter, that open into the combustion chambers and thus furnish a passage for the products of combustion through the flues and checkers to the stack. The drying operation is effected with wood fires and occupies a period of two weeks or longer, during which time the temperature of the ovens is raised to 250°F. Coal fires are then substituted for the wood, and the heating period is begun. About four weeks are required for this heating, during which time the temperature of the ovens is raised at the rate of about 25°F. each day. The ovens are then heated rapidly up to the coking temperature of 1700° F. or more. When available, gas may be substituted for the wood and coal for drying and heating the ovens.

Operation of the Ovens: Upon reaching the docks at the coke plant, of which there are two to a unit, the coal is unloaded from the barges by means of grab buckets (6-ton) which drop it into the hoppers of crushers. These hoppers are provided with 2½-inch cataract screens, so that only that portion of the coal that is too coarse for coking passes to the crushers.

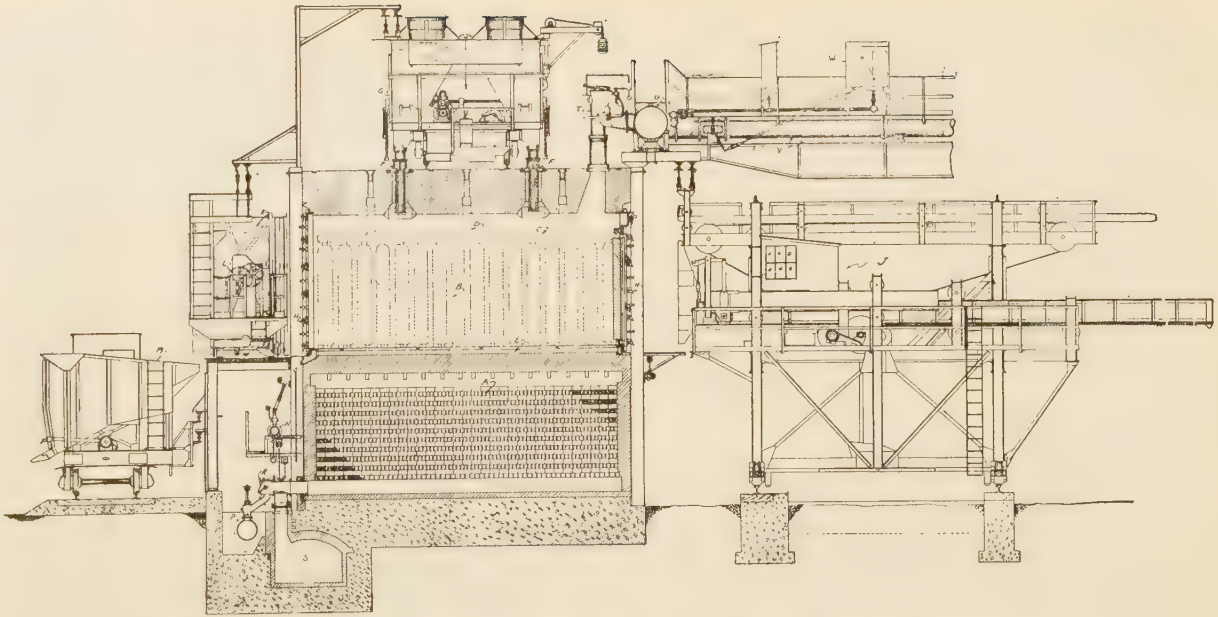


FIG. 33. Cross Section of Battery Showing Half of an Oven and all Equipment for Operation.

A. Checker Chamber.
B. Combustion Chamber.
C. Horizontal Flue.
D. Cross-over Flue.
E. Gas Duct for Coke Oven Gas.
F. Coal Inlet.
G. Hoppers of Larry Car.
H. Oven Doors.
J. Door Lifting and Pushing Machine.
K. Coke Guide.
L. Door Lifter.
M. Coke Watering Car.
N. Coke Oven Gas Main.
P. Producer Gas Main.
R. Air Valve.
S. Stack Flue.
T. Off-take.
U. Collecting Main.
V. Cross-over Main.
W. Gas Pressure Regulator.

FIG. 34. View of Ovens—Pusher Side.

FIG. 35. View of Ovens—Coke Side.

FIG. 36. View of Top of Ovens, Showing Coal Larry, Off-takes, and Collecting Mains with Final Coolers and Benzol Scrubbers in Middle Back Ground.

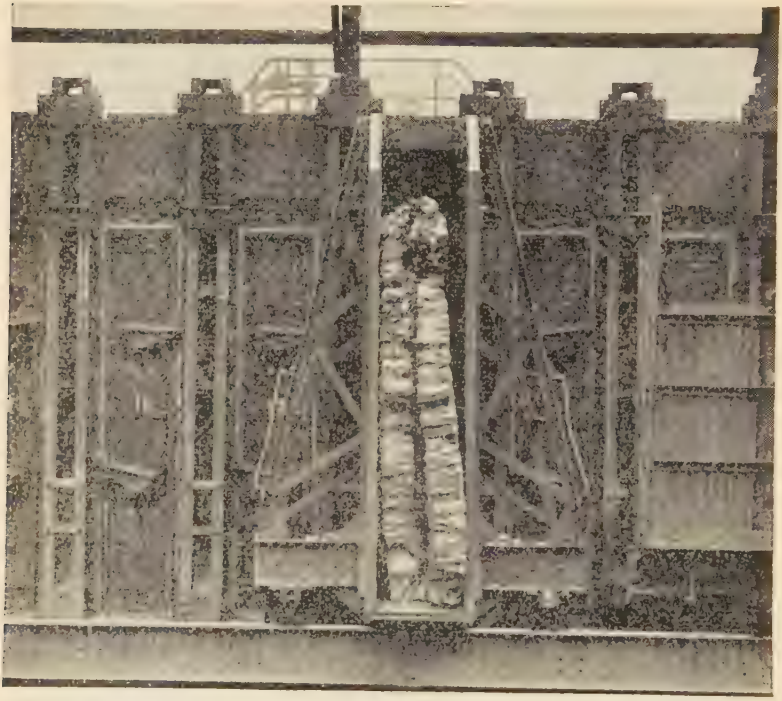


FIG. 37. View of coke being pushed from oven, showing central line of cleavage and block-like structure of the coke.

Here this coarse coal is crushed to lumps 2½ inches, or smaller, in size, and falls, together with that from the cataract screen, upon a conveyor belt and is carried to the eight bunkers, each of which is located above and between two batteries of ovens. These bunkers have a capacity of 4,000 or 4,500 tons each, so that four bunkers contain, when filled, enough coal to supply one unit for 24 hours. From the bunkers the coal is charged into the ovens by means of larry cars that travel lengthwise of the batteries and on top of the ovens. Each larry holds a single oven charge, and is so constructed that the coal is measured accurately by volume. From the larry, which has the form of four large funnels, the charge is dropped into the oven through the four charging holes, the doors of the oven having been previously set in place and luted with a mixture of loam or clay and coke dust. A reciprocating leveling bar, carried on the pushing machine, is then inserted through a small opening at the top of the door on the narrower end of the oven, and the peaks of coal are leveled to a uniform depth, thus filling the oven to within about 10

inches of the top. Finally, all openings to the oven are closed and sealed, the valve or damper to the gas collecting main is opened, and the coking process, which lasts for a period of 19 hours or less, begins. The heat for coking being supplied from the heating chamber by conduction through the walls of the oven, coking proceeds from both sides of the oven toward the middle, with the result that a marked plane of cleavage is produced vertically down the center of the whole charge. This fact gives to the coke a short, block-like structure that distinguishes it from beehive coke, which, as previously noted, has a long columnar structure. At the end of the coking period the connection between the off-stake and the collecting main is closed; the doors of the oven are moved to one side by mechanical devices for the purpose, and the coke is pushed out of the oven from the narrower end by means of a ram mounted upon the pusher previously mentioned. The coke falls into a side-dump hopper car; is carried therein to a quenching, or watering, house, of which there is one at each end of a row of batteries; is there watered by an overhead spray until well blackened, but still hot enough to dry itself; and is then discharged into an inclined dock or bin. Here it is allowed to become dry and to cool somewhat, after which period it is permitted to fall upon a large belt conveyor and is carried up an incline to the screening house. The coke then falls upon an incline screen made up of revolving discs, which is known as the rotary Grizzley screen. This screen separates the coarse furnace coke from the fines, which are then passed over ¾-inch shaker screens to separate the breeze or dust. The screens drop their materials upon conveyor belts, which deliver them to railroad cars, the small sized coke remaining on the shaker screens being added to the furnace coke on the way to the cars. At this plant all the dust is used under boilers to generate steam for use at the plant. The volatile products from the coal pass out of the oven and are conducted through pipes to the by-product plants, of which there are two, one for each unit.

Order of Charging and Pushing the Ovens: The preceding paragraph describes the process and its operation as carried out for each individual oven. In practice, however, each battery or a series of batteries must also be considered as an operating unit. One of the most important items in this connection is the order of charging and pushing the ovens of a battery, the reasons for which are apparent from a consideration of the heat requirements of the charge at different periods, or stages, of the coking process. Before this process can begin, the hydroscopic water must be driven off and the temperature of the coal must be raised to its fusion point. With the coal used at this plant, this temperature is in the neighborhood of 410° C. (770° F.). Beginning with the fusion of the coal, fixed gases begin to be given off, and as the temperature rises through the range from this point to about 600° C. (1100° F.), these are followed by condensable compounds, which in turn are succeeded by fixed gases,

mainly hydrogen and methane, until at about 950° C. (1950° F.) all the volatile matter of the coal has been driven off and the coking process is complete. The reactions that take place during the second, or coking, stage of the process are now recognized by investigators as exothermic, consequently very little, if any, heat is required to complete the period after the coal has once reached the fusion temperature. From this and other considerations, it is seen that the first period requires much more than half of all the heat to be supplied from an external source. In the by-product oven, coking proceeds from the walls of the oven at a rate which varies with the temperature of the heating chamber, so that, except at the beginning and the end, all three stages are occurring simultaneously in the oven, and the coking time can be controlled through the heating chamber. These conditions tend to equalize the rates at which the external heat may be supplied, but it is still plain that the first half of the time a charge is being coked requires more heat than the latter half. Therefore, to secure the highest efficiency with a uniform fuel consumption, adjacent ovens cannot be charged successively. Various plans for charging the ovens have been proposed and tried, but the scheme that has been proved most efficient at this plant is that known as the Marquard Pushing Cycle, which was originated and patented by Prof. W. B. Marquard. As the method is employed at this plant, the ovens of each battery are divided into two series and numbered 1A, 2A, 3A .... 31A or 32A, 1B, 2B, 3B .... 30B or 32B, and the pushing cycle is composed of 3 batteries or six of these series. Now, the general pushing order for a cycle is 1, 3, 5, 7 .... 31, 2, 4, 6, 8 .... 32, pushing the A's and B's alternately. So, the actual sequence of pushing is: Bat. 1, oven 1A, oven 1B; Bat. 2, 1A, 1B; Bat. 3, 1A, 1B; Bat. 1, 3A, 3B .... Bat. 3, 31A, 31B; then, Bat. 1, 2A, 2B; Bat. 2, 2A, 2B; Bat. 3, 2A, 2B; Bat. 1, 4A, 4B .... Bat. 3, 32A, 32B. With this order, the charges in the ovens adjacent to an oven being pushed are about half coked, and the difference in the ages of the adjacent ovens is very slight. This equality in the ages of adjacent ovens, gives a more uniform heating, which results in better coke structure and more nearly uniform by-product operations, and saves, in gas used for coking, about 60 B. t. u. per lb. of coal coked over former methods of pushing.

SECTION IX.

THE BY-PRODUCT PLANT.

The Volatile Matter of Coal is a very complex mixture. It may be roughly divided into three classes of substances, based on their state at ordinary temperatures; namely, the fixed gases, or those substances that are gases at ordinary temperatures, the liquids, and the solids. The fixed gases are hydrogen, H_2; methane, CH_4, also known as marsh gas; ethane, C_2H_6; propane, C_3H_8; butane, C_4H_{10}; ethylene, C_2H_4; small amounts of propylene, C_3H_6; butylene, C_4H_8; acetylene, C_2H_2; carbon dioxide, CO_2;

carbon monoxide, CO; hydrogen sulphide, H_2S; nitrogen, N_2; oxygen, O_2; and ammonia, NH_3. The vapors that are liquid at ordinary temperatures are benzene, C_6H_6; toluene, $C_6H_5CH_3$; xylene, C_6H_4 $(CH_3)_2$; carbon disulphide CS_2; and aqueous vapors. Among the vapors that are solid at ordinary temperatures, are naphthalene, $C_{10}H_8$; phenol, also known as carbolic acid, C_6H_5OH; anthracene, $C_{14}H_{10}$; and many others, all of which, together with heavy pitch-like substances, soot carbon, and small amounts of many of the more volatile liquid compounds cited above, enter into and make up the tar.

Gas Mains and Coolers: All these substances pass out of the ovens through up-takes at their narrower ends and into the U-shaped gas collecting main that extends above and parallel to a battery. The gases and vapors enter this collecting main at a temperature of about 400° C., and under a uniform suction of about .078 inch (2 mm.) of water, which is kept constant by means of a Northwestern gage governor and valve. From the collecting main, the gas is conducted by two pipes to a large main, known as the suction main, which serves as a common main for one half of a row of six batteries. This suction main leads to the primary coolers. In passing through these mains, the temperature of the gases drops to about 75° C., at the inlet to the primary coolers. This reduction in temperature causes much of the heavy tar vapors to condense in the mains, and it is found necessary to maintain a system for flushing the collecting mains in order to keep them clear of pitch and carbon stoppages. Formerly, mixtures of tar and ammonia liquor were employed for this purpose, but recent practice involves the use of tar free liquor, which is sprayed into the mains at the points most liable to be clogged. The requirements for this flushing amount to approximately 250 gallons of weak liquor to be circulated through the gas mains for each ton of coal carbonized in the ovens. The primary coolers are large rectangular tanks provided with tubes through which water circulates, while the gas, in its passage through the cooling chamber, is brought into intimate contact with these pipes. The gas leaves these coolers at a temperature of about 32° C. The cooling of the gas in its travel from the ovens through the gas mains and primary coolers results in the condensation of about 95 per cent. of all the tar and water vapor. The condensation takes place about as follows: 50 per cent. in the collecting mains and cross-over mains, 35 per cent. in the suction main, and 10 per cent. in the primary coolers. The condensing vapors carry with them all of the fixed ammonia in the gas, which amounts to about 15 per cent. of the total ammonia.

Separation of the Tar and Ammonia Liquor: These condensed liquids, composed of about 70 per cent. tar and 30 per cent. ammonia liquor, are conducted through pipes to large tanks known as the hot drain tanks, or tar wells, where, by means of baffles, the ammonia liquor is roughly separated from the tar, and the former is pumped back into the gas mains for flushing. The remainder of the liquor and the tar are pumped to separating tanks. In these tanks the tar and liquor, the former of which

has a specific gravity varying from 1.15 to 1.17 at 15° C., while the latter is little, if any, heavier than water, are allowed to separate by gravity, when the liquor is drained off into storage tanks and the tar is pumped also into storage tanks. From these storage tanks the tar, which is composed of water, 2 per cent., pitch, 62 per cent., and heavy oil, 33 per cent., and has a heating value of about 16,200 B. t. u. per lb., is withdrawn to a small loading tank from which it is loaded by gravity into tank cars as it is required for shipment; but since the semi-direct process for the recovery of ammonia is employed, the ammonia liquor, containing about 1.1 per cent. of ammonia, is pumped to ammonia stills. Here, the liquor is brought into contact with steam heated lime water, which liberates the ammonia. This ammonia gas is then conducted through cast iron pipes back to certain points in the gas mains, where it is disposed of in a manner to be described later. If desired, the ammonia vapors may be condensed to produce concentrated ammonia liquor. For operating these stills exhaust steam from various engines in the plant is used.

Compressors and Tar Extractors: After the gas leaves the primary coolers, it enters a number of positive exhausters (Connersville Exhausters) which produce a suction of 15 inches of water on the entering side and compress the gas to a pressure equivalent to 50 inches of water on the discharge side. This pressure is required in order to force the gas through the apparatus succeeding, the first of which are the P. and A. (Pelouze and Audouin) tar extractors. In each of these extractors the gas stream, by means of a perforated plate, is broken up into innumerable small jets which impinge upon the cold surface of a plate immediately behind the perforated plate. The impact causes the very fine particles of tar to collect on the impact plate, and the tar, thus accumulating, runs off the plate and out of the apparatus through a sealed overflow at the bottom. In these apparatus it is necessary to maintain a constant differential pressure of about 8 inches of water, and since the holes in the perforated plate tend to become closed by the more viscous of the tarry substances, thus causing an increase of the pressure, special means must be employed to overcome this tendency. At this plant the desired result is accomplished by lowering the tar level in the bottom of the apparatus, thus exposing more holes as those in use become clogged. The tar level is controlled by means of a pressure gauge and automatic regulator attached to the gate valve through which the tar passes in flowing out of the apparatus. The tar extracted by this machine amounts to about 5 per cent. of the total tar originally carried by the gas.

Recovery of Ammonia: The temperature of the gas, now about 38° C., having been raised about 6° C. by compression in the exhausters, is brought to about 55° C. by being forced through preheaters, which are cylindrical steel tanks containing steam coils. This preheating is necessary to prevent the accumulation of water in the saturators and to accelerate the reaction, between the ammonia and the dilute sulphuric acid, that occurs

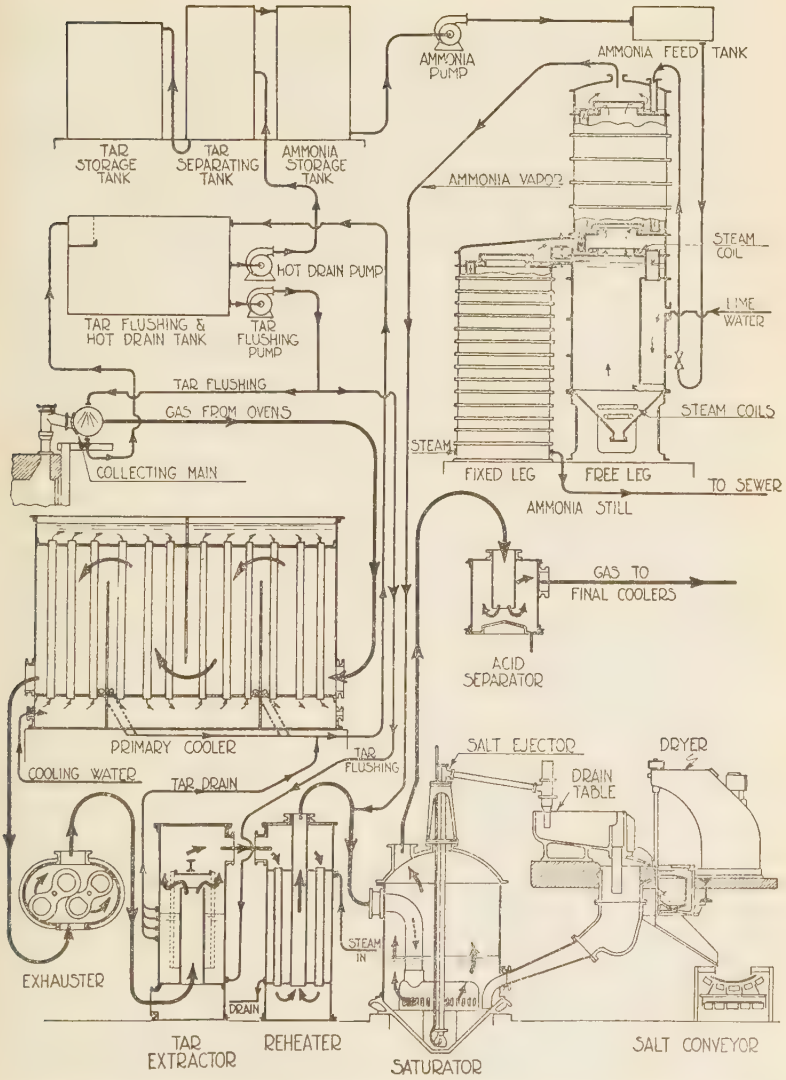


FIG. 38. Flow Sheet Showing Separation of Products from and Course of Volatile Matter from Ovens to Final Coolers. (Courtesy Koppers Co.)

in them. These saturators, of which there are ten or twelve to a unit, are large lead lined steel pots containing a 6-per cent. solution of sulphuric acid, through which the gas is forced in tiny bubbles. This gas, it is to be noted, contains all the ammonia recovered from the coal, for that which was liberated in the ammonia liquor stills, previously described, has been introduced into the gas mains just after the latter leaves the preheaters. In this way all the ammonia given off by the coal in coking is brought into direct contact with the dilute acid, with which it immediately reacts to form ammonium sulphate, $(NH_4)_2\ SO_4$. This salt dissolves in the water with which the acid was diluted, but, when the baths become saturated, it is precipitated and settles to the bottom, where it is forced through siphon ejectors by means of compressed air to elevated draining tables, also lead lined. From the draining tables, the salt is periodically removed, placed in centrifugal dryers, and whizzed for fifteen minutes, which process removes nearly all the water, the salt retaining about 2.5 per cent. of its own weight of moisture. The mother liquor derived from the drying operations, as well as the wash water used to free the crystals of the slightly acid mother liquor, flows back into the saturators, while the salt is scraped off the copper screen plates of the centrifugal machines with a mechanical device and delivered through a chute to a belt conveyor, which carries it into the storage rooms. Here the salt may be transferred with grabs directly to a stock pile, or be passed through a final dryer, where it is brought into intimate contact with hot gases. The main object of the final drying is to prevent caking, and to accomplish this object the moisture content should be reduced to .25 per cent. or less. The dryer delivers the salt to a pit, from which it is removed with grab buckets either to a stock pile or, if to be shipped at once, to the hopper of a sacking machine.

Debenzolating the Gas: In bubbling through the liquid in the saturator, the gas tends to carry a little of the acid along with it. Hence, from the saturator the gas passes into an acid separator. Its temperature here is about 54° C. which is much too high for the complete separation of the benzene and its homologues. Therefore, the gas is put through final coolers where its temperature is lowered to 30° C. These coolers are tall steel towers, about 100 feet in height. In them the gas is brought into direct contact with cold water, which is introduced at the top, while the gas enters at the bottom and leaves at the top. From these coolers the gas is forced through 3 or 4 benzol, or oil, scrubbers in series. Like the coolers, these scrubbers are large steel towers, in which the principle of counter currents is employed throughout. They are filled with a kind of checker work of wooden slats. A product from the refining of petroleum, (or of tar), known as straw oil or wash oil, with a distilling temperature ranging from 270° to 340° C., is sprayed into the top of the washers, where it trickles down over the wooden checker work and is thus brought into intimate contact with the ascending current of gases. The oil absorbs the benzene, toluene, xylene, naphtha and naphthalene, becoming saturated on absorbing about

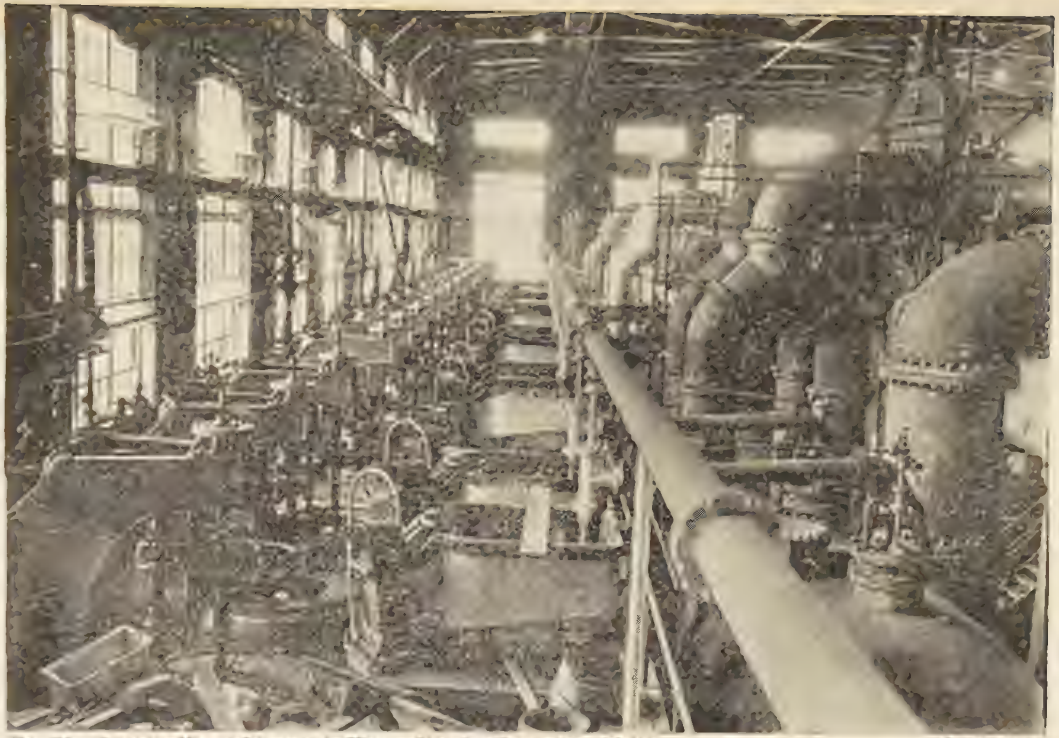


FIG. 39. Interior View of Ammonia House, Showing Saturators (right), Draining Tables (center) and Centrifugal Dryers (left)

3.5 per cent. of its own weight, and removing 92 per cent. or more of the total amount of these products in the gas. The entire removal of the naphthalene at this point is of great importance, because, if any remains in the gas, it crystallizes out and clogs the gas lines. From the scrubbers, the oil carrying the benzene, toluene, etc., is pumped to the benzol plant, which serves both units of the plant, while the gas, now freed from all except its fixed gases, is divided, about 36 per cent. being sent to the fuel lines to heat up the ovens and the remainder to the booster station, where it is compressed by steam turbo-blowers and delivered to the mills as surplus gas. The loss in heating power of the gas from a given quantity of coal, due to the removal of the by-products, amounts to about 5.8 per cent.

SECTION X.

THE BENZOL PLANT.

Light Oil: At the benzol plant the wash oil, carrying in solution the benzene, naphthalene, and their homologues, is first delivered to the light oil, or wash oil separating, stills. In order to conserve as much heat as possible, the inflowing wash oil is made to serve as a condensing liquid for the vapors from the still and as a cooling medium to the outgoing debenzolized wash oil. For this purpose, the incoming oil is made to flow successively through what are known as vapor-to-oil and oil-to-oil heat exchangers. After leaving the heat exchangers, the oil passes to preheaters, or superheaters, in which its temperature is raised to about 145° C. and much of the benzol is vaporized. The oil then passes to the stills, where it comes into direct contact with steam, which drives off the higher boiling oils and naphthalene. Since the wash oil has a much higher boiling point than the hydrocarbons it is desired to recover, only a small portion of it escapes from the stills. The vapors from the stills, after passing through the vapor-to-oil heat exchangers, are condensed in "light oil" condensers. The light oil, with the water condensed from the steam that escapes with it from the stills, flows into decanters, where the water separates by gravity. From the decanters the light oil is pumped to the "daily production tanks" for temporary storage. The wash oil, which is not vaporized, flows from the bottom of the stills and is conducted to heat exchangers, and then to water coolers where its temperature is lowered to 30° C. From these coolers it is pumped back to the oil scrubbers, and can be used repeatedly. However, there is a daily loss of approximately 2 per cent. The requirements for carrying on this continuous process call for the circulation of about 135 gallons of wash oil per net ton of coal coked. Hence, the total circulation for this plant is normally more than 1,700,000 gallons of wash oil per day.

Composition of the Crude Light Oil: The crude light oil obtained from the light oil stills, as described above, consists, on an average, of about 89 parts of light oil and 11 parts of wash oil. Light oil is a term

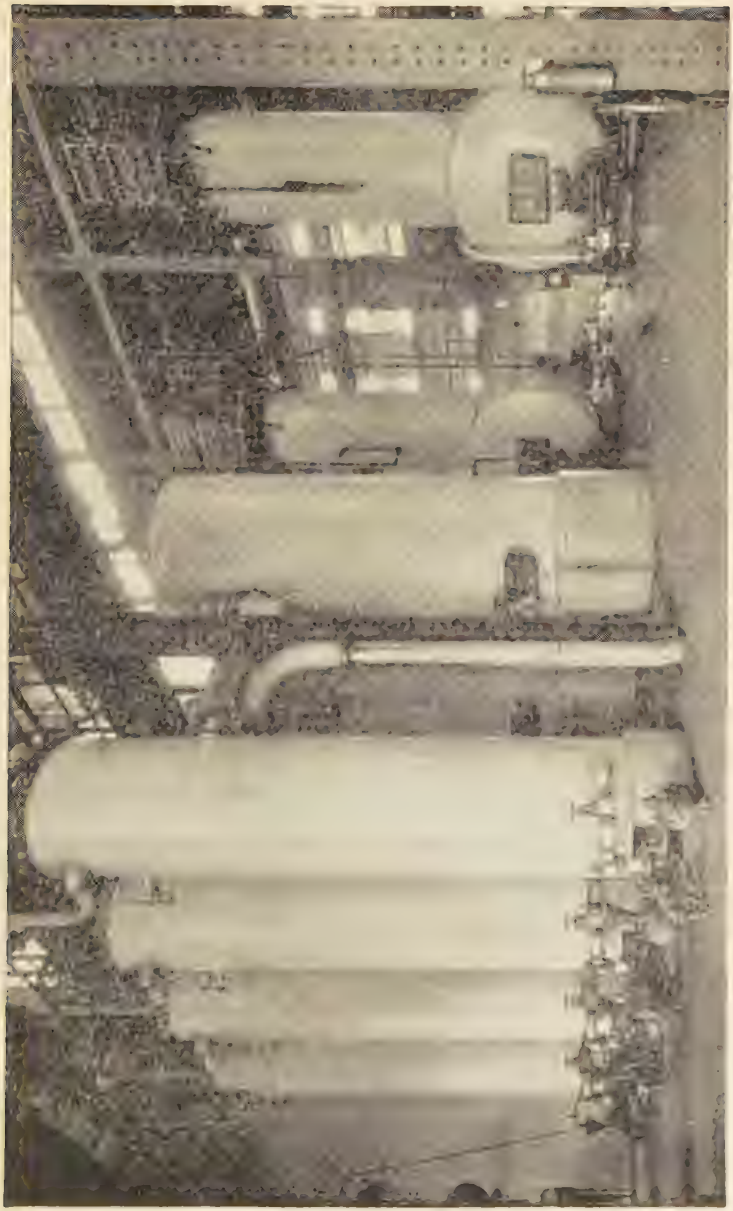


FIG. 40. View of the Benzol Plant, Showing Light Oil or Separating Stills (left) and Two Pure Stills (right.)

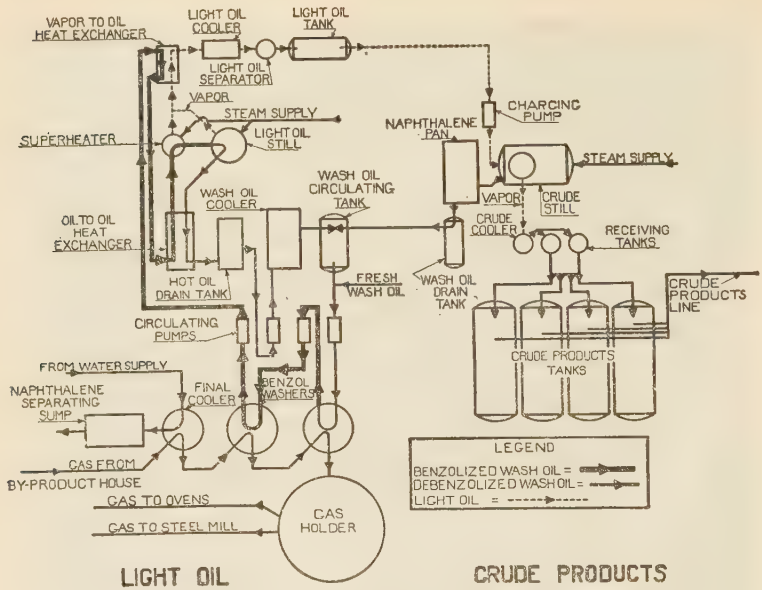


Fig. 41. Flow Sheet of Benzol Plant—Light Oil and Crude Products.

used in the by-product industry to designate the mixture of all those condensable products derived from the coking of coal whose boiling points do not exceed 200° C. The specification governing its composition is that, when subjected to the standard distillation test, 100 per cent. of the oil shall distill at a temperature of 200° C. As obtained in the coke works, it consists principally of benzene and toluene; but it also contains some xylene and other heavier hydrocarbons, the separation of which is not attempted on the first distillation. Consequently, the products heavier than toluene are obtained as fractions known as light and heavy solvent naphtha. On this basis, and assuming that the cuts are made at the customary temperatures, the light oil will yield on a single distillation the following products in about the proportions shown:

Crude Benzol	About	70	per cent.
Crude Toluol	"	17	"
Crude Light Solvent Naphtha	"	7	"
Crude Heavy Solvent Naphtha	"	6	"

The naphthalene collected in the scrubbers remains with the wash oil, and must be recovered by crystallization. In order to begin the separation of the crude light oil, into its various constituents, it is pumped from the light oil, or daily production, storage tanks to the crude stills.

Construction and Principles of the Still: The crude still consists of three sections. The lowest section is a horizontal cylinder provided

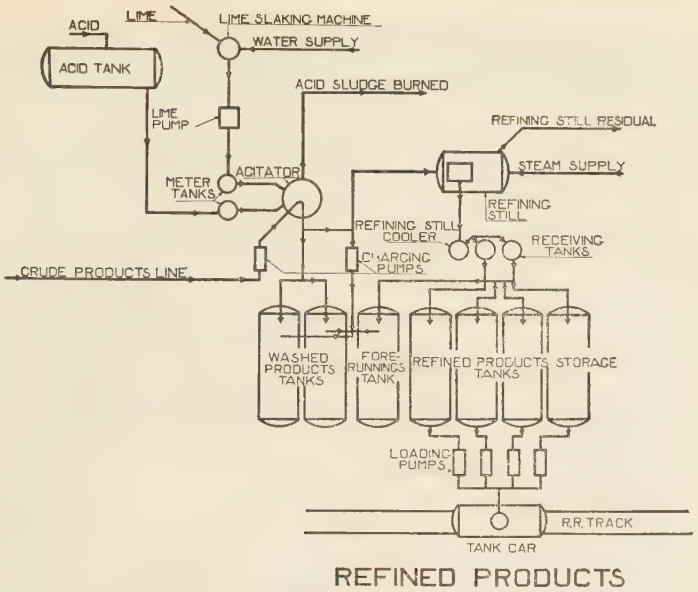


Fig. 42. Flow Sheet of Benzol Plant—Refined Products.

with steam coils, and has a capacity of 20,000 gallons in the case of the older stills or 35,000 gallons in the case of the newer stills; the second part, called the fractionating column, is a vertical column mounted upon this cylinder and composed of thirty-one bell sections for scrubbing the vapors as they pass upward; the third part, mounted on top of the column and called the dephlegmator, is a short horizontal cylinder that contains a number of water cooled pipes and acts as a partial condenser. The separation of light oil into its component oils is effected by taking advantage of their different boiling points. As the temperature of the light oil is raised and approaches the boiling point of the first runnings, this liquid is vaporized and passes up through the column; a portion of the other oils with higher boiling points is also vaporized, but is condensed before reaching the top of the column. There are thus two movements in the fractionating column and dephlegmator, namely, the vapors going upward and the condensed oils flowing downward into the still. The vapors are thus forced to pass through the return oils, which aid in condensing the vaporized oils of higher boiling points and permit only the lighter vaporized oils to reach the top of the dephlegmator, where they are condensed and flow from the still through a manifold into the storage tanks. As the temperature of the still is raised, therefore, the benzol, toluol, etc., is successively vaporized and condensed, and flows from the still. However, it is impossible to separate, absolutely, the benzol from the toluol, since, before the benzol is completely driven over, some toluol will be carried along with it. It is likewise impossible to separate

absolutely one from another the other constituent oils. Hence, it is only aimed to separate roughly the light oil into what are termed fractions. When a complete fractionation of the oil is to be made, these fractions, designated in the order in which they are made, are as follows: Fore Runnings, Crude Benzol, Crude Toluol, Crude Light Solvent Naphtha, Crude Heavy Solvent Naphtha and Still Residue. Each fraction is stored in a separate tank.

Operation of the Crude Still: The details of the operation of the crude still are as follows: Using the smaller stills, 20,000 gallons of light oil are charged. The temperature is gradually raised, and approximately 1,600 gallons of the light oil are vaporized and condensed. This product, known as the fore runnings and consisting of benzol containing approximately 3 per cent. carbon disulphide, is conducted into the fore-runnings storage tank. The next product is crude benzol. The still is continued on this fraction until a test shows that a certain per cent. will distill over at a given temperature, usually 100° C. A toluol fraction may then be collected until a test shows that a certain percentage will distill over at 130° C. The next product is the light solvent naphtha, which is collected until the flow of oil is very small, at which point, and continuing throughout the operation, the still is maintained under partial vacuum. The oil in this fraction is collected until a certain per cent. will distill over at a given temperature, usually 160° C., when heavy solvent naphtha is produced until a test shows that 90 per cent. will distill over at 205° C. The number of fractions and the exact point at which the cut is made in each case depends upon the final products desired. The residue in the still, consisting of wash oil and naphthalene, is drained into the naphthalene pans, where, upon cooling, the naphthalene separates as a solid. The wash oil is removed by a centrifugal machine, and the naphthalene is washed with hot water. It is sold as crude naphthalene, or refined and sold as C. P. naphthalene.

Washing the Products of the Crude Stills: Before these fractions of the crude still are subjected to further distillations, they are pumped to the washers and there agitated with sulphuric acid. The object of this treatment is to free the mixtures from unsaturated hydrocarbon compounds, paraffins and other impurities. These substances are acted upon and polymerized by the acid, to form substances that have very high boiling points. Some of these are insoluble in the mixtures and will settle out with the acid, forming a sludge. To carry out this washing, several thousand gallons (usually 10,000 gals.) of a crude product are transferred to a washer and a sufficient amount of 66-degree Baumé sulphuric acid to clean the product is added gradually. The exact amount of the acid used with each charge, or the proportion of acid to product, depends upon the wash test designated by the specifications, C. P. products requiring the most. The contents of the washer are agitated for about twenty minutes and allowed to stand for about fifteen minutes to permit the sludge to settle to the bottom of the washer, when it is drawn off. This acid sludge

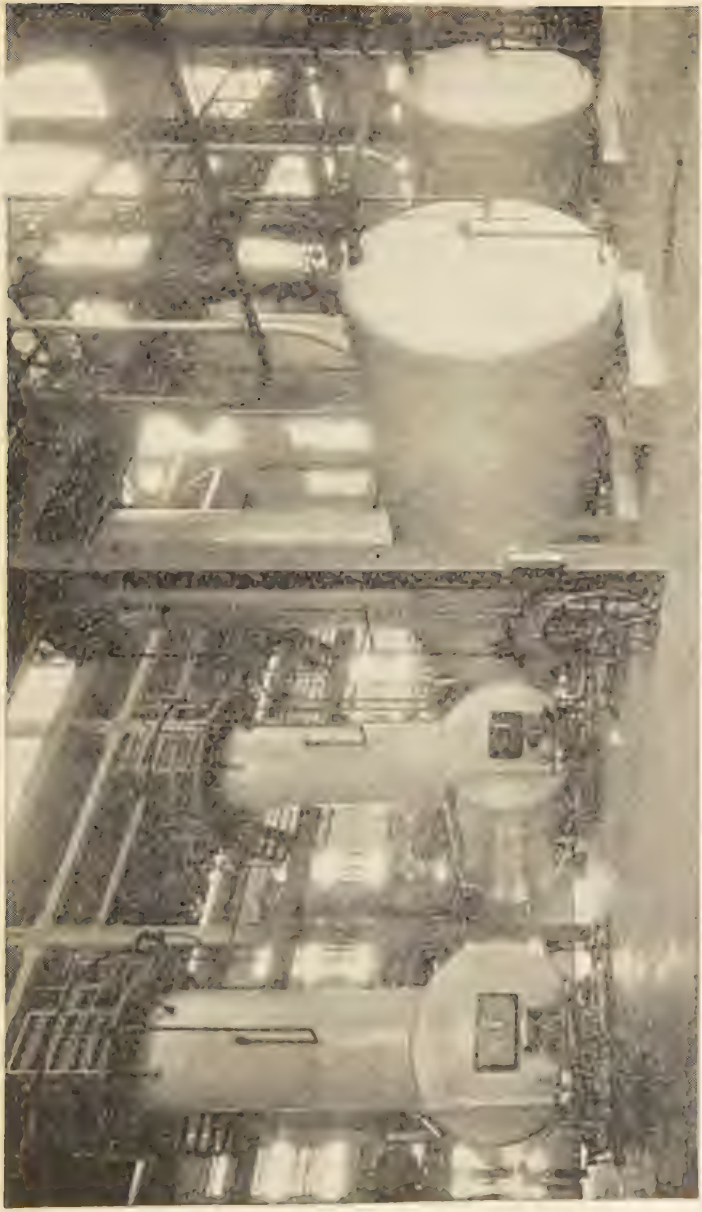


FIG. 43. View of Benzol House Showing two Refining Stills (left) and two Crude Stills (right).

is a waste product and is usually disposed of by burning. For the purest products the mixture may be washed with acid again in the same manner. After the use of the acid, the mixture is washed with 10-per cent. caustic soda solution or milk of lime until the last trace of acid is neutralized, when this material is allowed to settle and is drawn off. The washed product is then transferred to the refining still.

The Refining Stills: The construction and operation of the refining still is practically identical to that of the crude still, except that the dephlegmator is horizontal and the vapors pass over its tubes, instead of through them. However, while the fractions of the crude still consist of a mixture of several different compounds, the refining still may be operated so that at least one fraction will be a pure compound, as is shown by the following data:

Still Charge—17,676 Gals. Washed Crude Still Benzol Fraction.

Fraction.	Time.	Gals.	Product.
1	12¾ hrs.	1440	R. R. (Rerun) Benzol—Benzol containing Carbon Bi-sulphide.
2	31 "	10950	C. P. Benzol.
3	2½ hrs.	790	R. R. (Rerun) Benzol—Greater portion Benzol, part Toluol.
Residue		4496	Principally Toluol.

Fraction 2, being pure benzol, is not further treated, and is ready for the market. The rerun (R. R.) benzol fraction, 1 and 3, and the residue are stored in separate tanks. When a sufficient quantity of a R. R. fraction has accumulated, the pure still can be charged with it and a C. P. (chemically pure) product obtained, as is shown by the following data:

Still Charge—18,200 Gals.
R. R. Benzol.

Fraction.	Time.	Gals.	Product.
1	16¾ hrs.	2550	R. R. Benzol—containing Carbon Bisulphide.
2	39 "	10900	C. P. Benzol.
3	10 "	1750	R. R. Benzol—Greater portion Benzol, part Toluol.
4	5 "	650	R. R. Toluol—Part Benzol, greater portion Toluol.
5	6½ "	1300	C. P. Toluol.
Residue		1050	Toluol and Solvent Naphtha.

Fraction 2 and 5, being C. P., are ready for the market. The other fractions are stored and, when a sufficient amount is collected, are distilled like the R. R. Benzol charge just described. It is not essential that the pure still be charged with a straight R. R., or 90-per cent. product, as a mixture of the two is often distilled as follows:

Still Charge—6800 Gals. 90-Per Cent. Washed Toluol.
10150 " R. R. Toluol.

Fraction.	Time.	Gals.	Product.
1	15¾ hrs.	1610	R. R. Benzol—greater portion Benzol, part Toluol.
2	29 "	5130	R. R. Toluol—greater portion Toluol, part Benzol.
3	24 "	6950	C. P. Toluol.
4	6¼ "	400	R. R. Toluol—greater portion Toluol, part Naphtha.
		2860	Residue—Toluol and Naphtha.

It is thus apparent that the light oil will eventually be completely worked up into its pure product. There is one exception, however, in that the light runnings containing the carbon bisulphide cannot be separated by fractional distillation. The crude carbon bisulphide benzol is the first 1600 gallons that come over in the crude still. This is placed in a separate tank, into which the forerunnings, or carbon bisulphide benzol, from the refining still is also collected. When 20,000 gallons of this product, containing approximately 3 per cent. of carbon bisulphide, is collected, it is placed in the crude still. The first 4000 gallons condensed is benzol containing 10 per cent. of carbon bisulphide, the remaining portion is 90-per cent. benzol, which is transferred to the crude 90-per cent. benzol tank. Only a restricted market has so far been found for the 10-per cent. carbon bisulphide benzol.

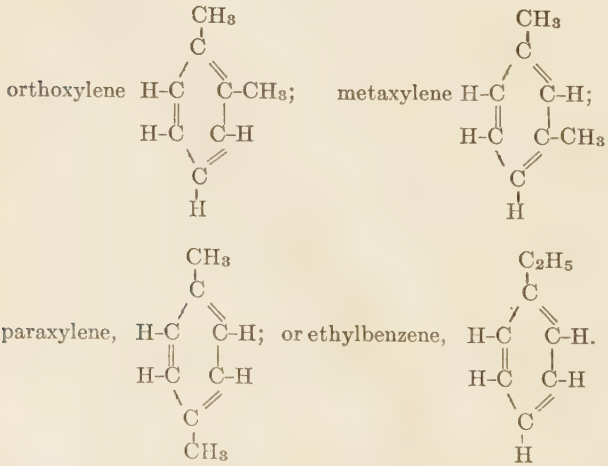
Other Products of the Refining Stills: It is not to be inferred from the preceding description that the refining stills are used only for the production of pure compounds, for, as a matter of fact, their chief output in normal times consists of refined mixtures, such as motor benzol. In making these refined mixtures, the procedure is similar to that followed for pure products, except that the number of fractions may be less and the points at which the cuts are made will be different. The composition of the mixtures, or the purity of the compounds in the case of pure products, is determined and controlled by suitable laboratory tests, chief of which is the boiling point or distillation test. As to the methods for conducting these tests, the student is referred to the published works upon this subject.[1] More information about the various refined products obtained from the refining stills will be found in the next section.

[1]See Methods of the Chemists of the United States Steel Corporation for the Sampling and Analysis of Coal, Coke and By-Products, published by Carnegie Steel Company, Pittsburgh, Pa.

SECTION XI.

SOME PROPERTIES AND USES OF THE RAW BY-PRODUCTS FROM THE COKE WORKS.

Characteristics of Benzol, Toluol and Naphtha: While the names benzol, toluol, xylol and naphtha are those commonly applied in commerce, chemical names used to designate corresponding pure compounds are benzene, toluene, xylene, cumene, etc. Naphtha is a mixture of several compounds, including xylene, cumene and others, so it has no chemical name. As previously indicated, these compounds are members of the aromatic, or benzene, series of hydrocarbons represented by the general formula C_nH_{2n-6}. The empirical formulas for benzene, C_6H_6, and toluene, C_7H_8, represent individual compounds, but these formulas for xylene, C_8H_{10}, and cumene, C_9H_{12}, represent series of isomeric compounds, which, though they are members of the same series and may have the same empirical formula, differ widely in properties. Thus, the formula C_8H_{10}, may represent



The chief physical properties of the first and more important members of the series are given in the following table, which will also give some idea of the method of naming the compounds:

Table 13. Some Members of the Benzene Series and Their Physical Properties.

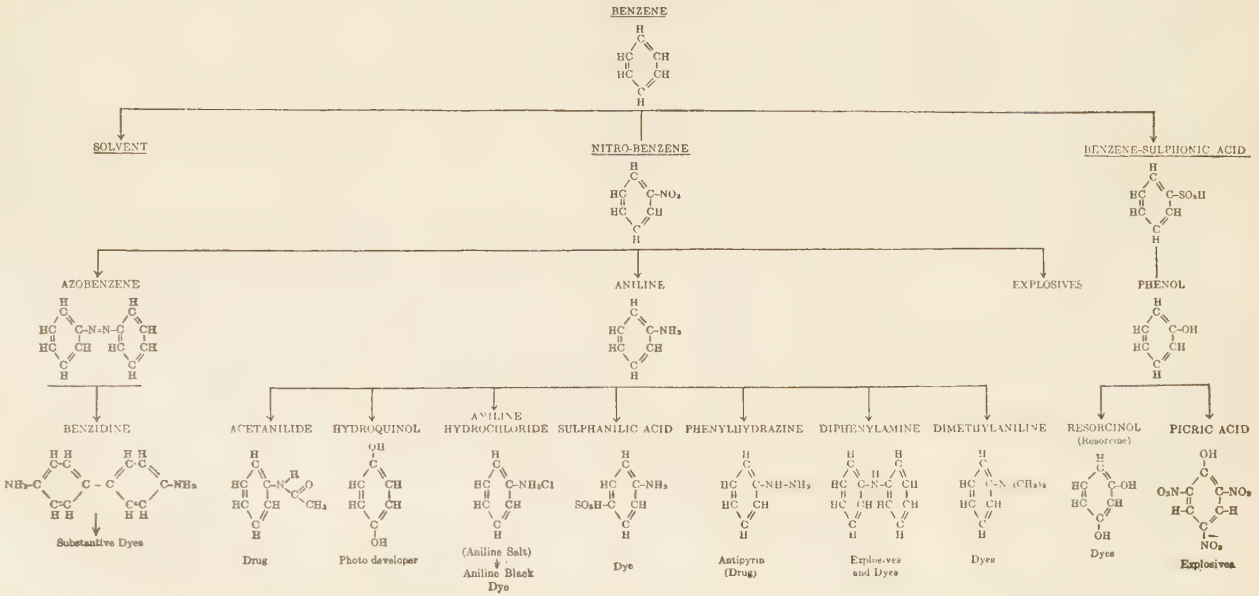
FORMULAS		NAME	State at Ordinary Temperature	Melting or Freezing Point °C.	Boiling Point °C.	Specific Gravity
Empirical	Rational					
C_6H_6	C_6H_6	Benzene	Clear Liquid	+5.4	80.4	.884 $\left\{\frac{15°}{4°}\right\}$
C_7H_8	$C_6H_5 \cdot CH_3$	Toluene or Methyl-benzene	" "	—92.4	110.3	.871 $\left\{\frac{15°}{4°}\right\}$
C_8H_{10}	$C_6H_4 \cdot (CH_3)_2$	Orthoxylene or Ortho-dimethyl-benzene	" "	—28	142.0	.893 $\left\{\frac{0°}{4°}\right\}$
		Meta-xylene or dimethyl-benzene	" "	—54.8	139.1	.87- $\left\{\frac{15°}{4°}\right\}$
		Para-xylene or dimethyl-benzene	" "	+13°	138.0	.880 $\left\{\frac{0°}{4°}\right\}$
	$C_6H_5 \cdot (C_2H_5)$	Ethylbenzene	" "	.....	136.0	.883 $\left\{\frac{0°}{4°}\right\}$
C_9H_{12}	$C_6H_3 \cdot (CH_3)_3$	Hemimellithene or v—Trimethyl-benzene	" "	.....	175.0	....
		Pseudocumene or as-Trimethylbenzene	" "	.....	169.5	.895 $\left\{\frac{0°}{4°}\right\}$
		Mesitylene or s-trimethyl-benzene	" "	.....	165.0	.865 $\left\{\frac{15°}{4°}\right\}$
	$C_6H_5 \cdot C_3H_7$	Normal Propyl-benzene	" "	.....	159.0	.867 $\left\{\frac{15°}{4°}\right\}$
		Cumene or Isopropyl-benzene	" "	.....	153.0	.866 $\left\{\frac{15°}{4°}\right\}$
$C_{10}H_{14}$	$C_6H_2 \cdot (CH_3)_4$	Prehitene or Tetra-methyl-benzene	.....	.....	.....	.....
	$C_6H_4 \cdot CH_3 \cdot C_3H_7$	Cymene or Methyliso-propyl-benzene	.....	.....	.....	.....
and so on to $C_{25}H_{44}$			.....	.....	.....	.....

Commercial Benzol: The term "benzol" is employed commercially in connection with the various mixtures of the benzene hydrocarbons. Pure benzene is usually marketed as "Chemically Pure", or "C.P.," benzol. The mixtures are generally designated as 90-per cent. washed benzol, 90-per cent. crude benzol, 80-per cent. washed benzol, 80-per cent. crude benzol, and so forth. The terms "washed" and "crude" denote whether or not the product has been washed with sulphuric acid to remove the various unsaturated compounds which are always present in the crude product. As a rule, most of these products are washed to a greater or less degree of refinement, according to the purpose for which they are required. The terms "90-per cent." or "80-per cent." refer to the amount of the fraction which will distill over up to 100° C. The lower this percentage, the greater will be the amounts of toluol and solvent naphthas present in the product. The 90-per cent. washed benzol will contain approximately 80 per cent. of benzol, 15 per cent. of toluol, and 5 per cent. of xylols and light solvent naphthas.

Uses of Commercial Benzols: Benzols have been largely used as solvents for fats, waxes, gums, and resins. Mixed with alcohol and ammonia, benzols of these grades make an excellent cleanser for the removal of grease and paint. Its solvent action on gums and resins makes it a valuable substance in the manufacture of paints, varnishes, and lacs, especially of enamel, bronze and aluminum paints, in which a neutral gum, or resin, is used to form the bases. The solvent action of these grades upon rubber makes them valuable in the preparation of cements and insulating varnishes. They dissolve sulphur mono-chloride, and are hence used in the cold vulcanization of rubber. Heavy benzol and solvent naphtha are employed in the preparation of enamels, wood stains, varnishes, and waterproofing materials, such as the rubberized cloth known as mackintosh. Certain grades may be used as a substitute for turpentine in paints intended to cover resinous woods. Naphtha, in particular, is important as a rubber solvent in the manufacture of rubber goods, and as a solvent for anthracene during the final purification of this substance with sulphuric acid. It is also used in the cleaning of clothing.

Motor Benzol: A product corresponding approximately to 80-per cent. washed benzol makes an excellent motor fuel for automobile engines, though up until 1919 it had not been extensively used as such in the United States. Inasmuch as the commercial use of pure benzol and pure toluol is comparatively limited, since the demand for explosives has decreased, fully 80 per cent. of all the benzol and toluol now produced in the United States is used as a motor fuel. For this purpose there is no necessity of separating the toluol from the benzol, and all of these two substances, together with practically all of the xylol, are combined in one product. This product is marketed as "Motor Benzol." Pure benzol, freezing at 5.4° C., congeals readily in cold weather, but the presence of the toluol and xylol in motor benzol lowers this freezing point so that cars may be satisfactorily operated during freezing weather. Gasoline to the amount

Table 14. Diagram Showing Some of the Products Derived from Benzene, Their Formulas and Their Uses.



of about 25 per cent. mixed with this product makes a mixture suitable for the coldest weather. Any carburetor adapted for gasoline can be used as well for motor benzol, but more air, or oxygen, is required in the explosive mixture with this fuel than with gasoline. When properly handled, motor benzol gives from 20 per cent. to 30 per cent. greater mileage than does gasoline. Mixed with gasoline in the proportions of 25 per cent. or more, it serves as an anti-knock compound. At the present time motor benzol is made under the following specifications:

Color	Water-white.
Distillation	Start 78° to 82°C.
	Finish not higher than 135°C.
Wash Test	No. 9, or better.

Sulphur content not to exceed 0.25%[1].

The wash test is made by agitating equal quantities, usually 20 cc., of the benzol and pure sulphuric acid in a glass tube and comparing the color with that of numbered standards, the first of which, No. 0, is perfectly clear, like pure water.

Properties and Uses of Pure Benzol, or Benzene: The chief physical properties of this very interesting substance have already been given. Concerning its chemical properties and uses, it may be said that it is one of the most interesting and useful compounds known to the chemical profession. This fact is more fully appreciated when it is known that it is the base from which such drugs as phenol, hydroquinon, antipyrin and acetanilid; such dye stuffs as resorcinol, benzidine, aniline, and indigo; and such explosives as nitrobenzol and picric acid are prepared. The relations of benzene to these compounds is best shown briefly by means of some such diagram as that on the preceding page.

To illustrate the reactions by means of which some of the more important compounds are derived from benzene, the following tables have been prepared:

Table 15. Reactions Showing How Aniline and Benzidine Are Derived from Benzene.

$$C_6H_6+HNO_3\ (H_2SO_4)=C_6H_5NO_2+H_2O\ (H_2SO_4)$$

Nitro Benzene.

$$2C_6H_5NO_2+4SnCl_2+4KOH=\begin{matrix}C_6H_5\cdot N\\ \|\\ C_6H_5\cdot N\end{matrix}+2SnCl_4+2H_2O+2K_2SnO_3$$

Nitro Benzene. **Azobenzene.**

$$C_6H_5\cdot NO_2+6HCl+3Fe=C_6H_5\cdot NH_2+3FeCl_2+2H_2O$$

Nitro Benzene. **Aniline.**

$$\begin{matrix}C_6H_5\cdot N\\ \|\\ C_6H_5\cdot N\end{matrix}+Sn\,Cl_2+2HCl=\begin{matrix}C_6H_4\cdot NH_2\\ |\\ C_6H_4\cdot NH_2\end{matrix}+SnCl_4$$

Azobenzene. **Benzidine.**

Substantive Cotton Dyes.

Table 16. Reactions Showing How Phenol, Picric Acid and Resorcinol May Be Derived from Benzene.

$$C_6H_6 + H_2SO_4 = H_2O + C_6H_5(H)SO_3$$

Benzene Sulphonic Acid.

$$C_6H_5(H)SO_3 + KOH = C_6H_5(K)SO_3 + H_2O$$

Potassium Benzene Sulphonate.

$$C_6H_5(K)SO_3 + 2KOH = K_2SO_3 + C_6H_5OK + H_2O$$

(Heated to fusion) **Potassium Phenate.**

$$2C_6H_5OK + H_2SO_4 = 2C_6H_5OH + K_2SO_4$$

Phenol.

$$C_6H_5OH + H_2SO_4 = H_2O + OH{\cdot}C_6H_4(H)SO_3$$

Phenol. **Para Benzene Sulphonic Acid.**

$$OH{\cdot}C_6H_4(H)SO_3 + 2KOH = K_2SO_3 + H_2O + C_6H_4(OH)_2$$

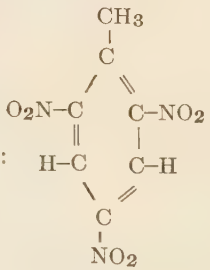
Metadihydroxylbenzene
or Resorcinol
(Resorcine)
Base of many colors.

$$2C_6H_5OH + 6HNO_3 = 2C_6H_2\langle^{(NO_2)_3}_{OH} + 3H_2O + 3O$$

Phenol. **Picric Acid.**

Uses of Toluene: One of the chief uses of toluene is found in the manufacture of high explosives. These are prepared by nitrating toluene. Both the di-nitro-toluene and the tri-nitro-toluene are used, but of these the latter, often referred to as T. N. T., is more important. In intensity of explosion it ranks below picric acid, derived from phenol, but is much safer to handle, because the acid has the property of reacting direct with metals to form picrates, which are very sensitive to shock, whereas T. N. T. does not form dangerous salts with metals and is not sensitive to mechanical shock. It is also replacing gun cotton, or nitrocellulose, in torpedoes, mines, etc.

Its formula is represented thus:

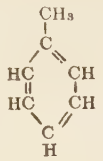


Since the molecule of T. N. T. does not contain enough oxygen for the complete combustion of the carbon atoms, it produces much smoke on burning or exploding. This defect is overcome by mixing with it some nitrate, preferably ammonium or lead nitrate. In addition to its use as an explosive, toluene is also the base from which saccharin, benzoic acid, many dyestuffs, and perfumes are prepared, as a glance at the accompanying diagram will show: (See Table 17.)

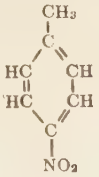
Commercial Toluol and Solvent Naphtha: Commercial toluol, often spoken of as 90-per cent. toluol, is a mixture composed mainly of toluol, 90 per cent. of which will distill at 120° C. and not more than 5 per cent. at 100° C. In the case of solvent naphtha, 90 per cent. distills at 160° C. and not over 5 per cent. at 130° C. These mixtures are often used instead of benzol, because they evaporate more slowly or because they have a higher flash point. Some of the industries in which their use is found advantageous are the manufacture of automobile tires, rubber cements, artificial leather, wood stains, paint and varnish removers, paints (as a substitute for turpentine) and special inks.

Table 17. Some Products Derived from Toluene, Their Formulas and Uses.

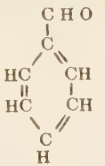
TOLUENE



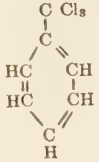
PARA NITROTOLUENE



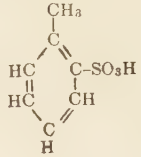
BENZALDEHYDE
(Benzoic Aldehyde)



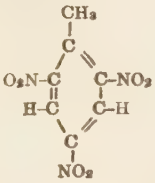
BENZENYL TRICHLORIDE



TOLUENE SULPHONIC ACID

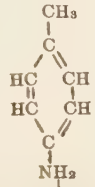


TRINITROTOLUENE
(T. N. T.)



Explosive

TOLUIDIN

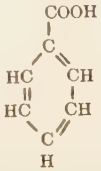


Dyes

Dye Stuffs

Perfumes

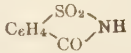
BENZOIC ACID



Food Preservative

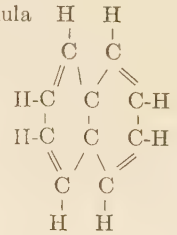
Dye Stuffs

SACCHARIN



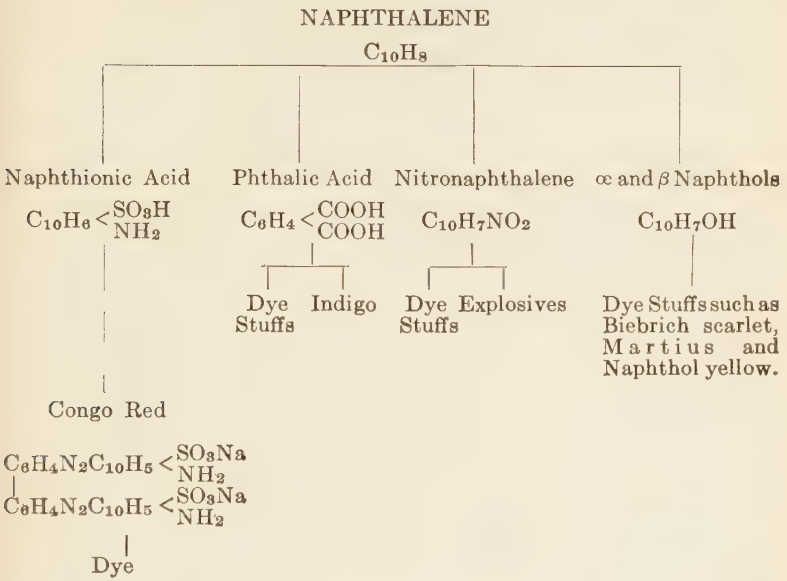
Substitute for sugar. No food value.

Uses of Naphthalene: $C_{10}H_8$ does not belong to the benzene series, C_nH_{2n}—6, but is the first member of a series represented by the general formula C_nH_{2n}—12, and by the structural formula



It is used as an antiseptic and insecticide, and is familiar to every one in the form of **moth balls.** But its real importance lies in the fact that it is the base from which many dyestuffs are prepared, chief of which is indigo. The steps by which this important dye is derived from naphthalene are about as follows: (1) Naphthalene, $C_{10}H_8$, is heated with fuming sulphuric acid and mercury, which acts as a catalytic agent, whereupon there is formed phthalic acid, $C_6H_4(COOH)_2$, (2) which, on being heated, passes into phthalic anhydride, $C_6H_4<\begin{matrix}CO\\CO\end{matrix}>O$ (3) from which phthalimide, $C_6H_4<\begin{matrix}CO\\CO\end{matrix}>NH$, is obtained with the aid of ammonia and heat (4). By oxidizing phthalimide with bleaching powder, anthranilic acid, $C_6H_4\cdot NH_2\cdot COOH$ is formed, (5) which is changed by treatment with monochloacetic acid to phenyl-glycine-ortho-carboxylic acid, $C_6H_4\cdot COOH\cdot NH\cdot CH_2\cdot COOH$, (6) by fusing this compound with caustic soda, indoxyl, $C_2H_4NH\cdot CO\cdot CH_2$, is formed and is readily oxidized by the oxygen of the air to indigotin, $C_6H_4\cdot NH\cdot CO\cdot C{=}C\cdot CO\cdot NH\cdot C_6H_4$, or indigo-blue. The following table will serve to show the many other dyestuffs that may be obtained from naphthalene:

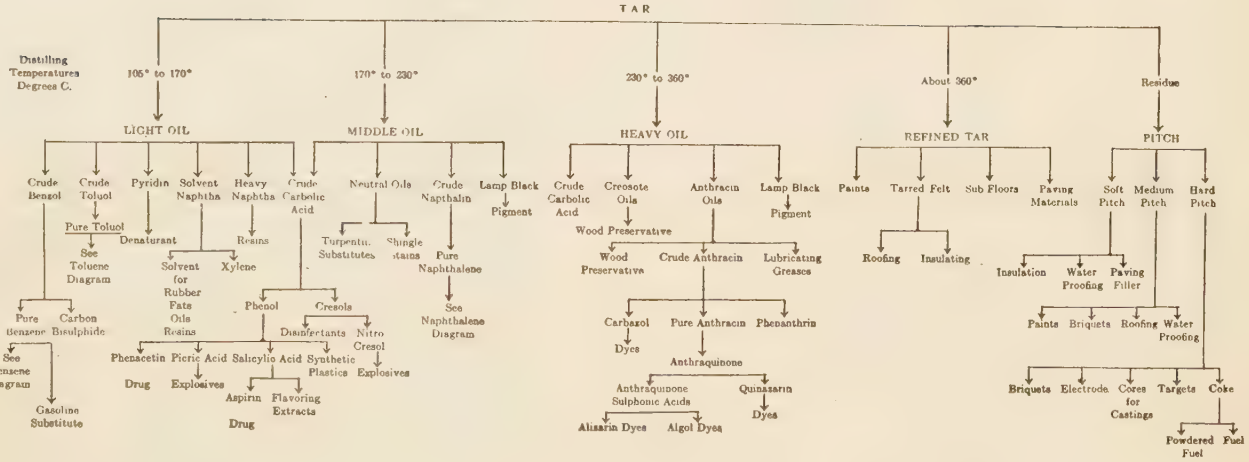
Table 18. Showing Some Products Derived from Naphthalene.



Tar: As obtained from gas works as well as from by-product coke plants, tar is a black, viscous, oily liquid, with a specific gravity that varies from 1.15 to 1.20, that from coke works having a gravity of about 1.18. It also varies a great deal in other respects, especially in composition. It is a very complex mixture; the number of its compounds have been estimated at about 300, only some of which have been isolated in the laboratory and but a very few in the commercial working up of the liquid. In the crude state it may be used as a fuel and for road dressing, but, by refining, it is made to yield a great number of products of great economic and hygienic importance. The refining of tar forms an industry by itself, which requires volumes to describe in all its details. Suffice it to say, that the refining of tar is essentially a process of fractional distillation, in which it is first separated roughly into several parts, which may then be further rectified into purer substances as shown in the following diagram, which is also made to indicate the uses to which the products are applied.

Ammonia, as concentrated ammonia liquor (NH_4OH and H_2O), is used in making anhydrous ammonia gas (NH_3) for refrigeration purposes and the aqua ammonia of commerce, used for cleaning. It is also used in

Table 19. Diagram Illustrative of the Refining of Tar.



the manufacture of baking soda and a large number of ammonium salts, such as ammonium chloride and ammonium nitrate. The last named salt is extensively used in the manufacture of explosives. By passing ammonia and air over heated platinum black, the former is oxidized to nitric acid, and large quantities of ammonium nitrate are now produced by this method. Ammonia is used extensively in dye works, and a considerable amount is consumed by chemists in analytical laboratories.

Ammonium Sulphate, $(NH_4)_2SO_4$, is a white crystalline salt, very soluble in water and easily decomposed by heat, beginning at 140° C., into NH_4HSO_4 and NH_3, and at a red heat into NH_3, SO_2 and H_2O. Unlike most ammonium salts, it cannot be sublimed. As obtained from the coke works, ammonium sulphate contains from .1 to 2.5 per cent. of moisture, and .3 per cent. or less of other impurities which it is impossible to exclude entirely. Formerly, coke works sulphate, though neutral when freshly made, would become acid on aging to the extent of .05 to .1 per cent., but recent improvements in practice have made it possible to produce regularly salt that will remain neutral. It is used for a number of purposes, including the preparation of ammonium persulphate and nitrate, but its great field of usefulness is exhibited as a commercial agricultural fertilizer. William H. Childs of the Barrett Co., who has made a careful study of the use of the salt for this purpose, speaks thus of it:

Use of Ammonium Sulphate as a Fertilizer: "Sulphate of ammonia is extensively used in ready mixed fertilizers, which is the form generally purchased by the American farmer. These usually contain acid phosphate and potash, together with sulphate of ammonia, tankage, cotton-seed meal, etc. Sulphate of ammonia is dry in its nature, and makes an excellent mixture as far as mechanical condition goes, with the added advantage that it does not react with the other fertilizer chemicals to cause loss of nitrogen or reversion of the acid phosphate, both of which points are claimed against nitrate of soda. The nitrogen in sulphate of ammonia is quick to act, is not easily leached out of the soil, and it continues its action over a considerable period, so that the growing plant is carried along to maturity without setback. Its only disadvantage is the tendency to exhaust the lime in the soil. While this point is apt to be urged by Agricultural Experiment Station men, it is really of minor importance because the actual amount of sulphate of ammonia in the usual fertilizer application is small, and its nitrogen is relatively so much more beneficial to the growth of the crop. The liming of the soil, which, of course, overcomes all objections, is urgently recommended by all Experiment Station advisers, and in large areas of the Eastern States is practically the foundation of profitable agriculture. On the other hand, in some soils, as in those of Southern California and parts of Texas, which tend to excess of alkali, the action of sulphate of ammonia is peculiarly beneficial. In some soils sulphur is lacking, so that the sulphur in sulphate of ammonia actually acts as a plant food."

CHAPTER V.

FLUXES AND SLAGS.

SECTION I.

FLUXES.

Smelting and the Functions of a Flux: Any metallurgical operation in which the metal sought is separated, in a state of fusion, from the impurities with which it may be chemically combined or physically mixed is called **smelting.** Since both these conditions with regard to impurities are usually present, smelting involves two processes; namely, the reduction of the metal from its compounds and its separation from the mechanical mixture. Many of these impurities may be of a highly refractory nature, and if they were to remain unfused, they would choke up the furnace, retard the separation of the metal and interfere in various other ways with the smelting. To render such substances more easily fusible is the **primary function of a flux.** Again, some elements, being reduced almost simultaneously with the metal, combine chemically with it, while other elements and some radicals, chemically combined with the metal in the raw materials, refuse to be separated from it, except there be present some substance for which they have a greater chemical affinity. To furnish a substance with which these elements and radicals may combine in preference to the metal is **the second function of the flux.**

The Selection of the Proper Flux for a Given Process is, then, chiefly a chemical problem and requires a knowledge of the chemical composition of all the materials entering into the process. With this knowledge in hand, the selection will be governed by well known physical and chemical laws, chief of which is the action of acids and bases toward each other and the fusibility of the various compounds thus formed. In general, if the matter to be fluxed is basic, such as lime, magnesia and other compounds of base forming elements, the flux must be acid, while if the impurities be acid, such as silica and phosphoric acid, a basic flux will be required. In most ores the impurities will belong to both classes with one or the other class, usually the acids, predominating. In a few iron ores the two classes of impurities are so well balanced as to render the ores self-fluxing, or by proper mixing they can be made so. In order to control fusibility, a neutral flux is sometimes required. The cost of the flux is also to be considered, hence the natural deposits of greatest purity that are easy of access and in

close proximity to the works are made use of. A brief discussion of the fluxes of greatest importance in the iron and steel industry follows:

Acid Fluxes: Silica is the only substance that may be classed as a strictly acid flux. For this purpose it is available as sand, gravel and quartz in large quantities and in a sufficiently pure state. In blast furnace practice, it is customary to employ acid open hearth or Bessemer slags or ores of high silica content when it is desired to increase the acids in the furnace, as, in this way, the metallic contents of these substances are recovered.

Alumina: Unlike silica, which is a strong acid under all conditions, alumina may perform either the function of an acid or a base, depending upon the conditions imposed. Thus, with silica, it forms aluminum silicate, and with a strong base, such as sodium, sodium aluminate. A marked peculiarity is its tendency to form, in conjunction with other bases, double salts with polybasic acids. As a rule, double silicates are more easily fused than those containing a single base. Alumina is seldom used intentionally as a flux, but it is present in nearly all raw material, hence unavoidable.

Basic Fluxes: The chief natural fluxes of this class are limestone and dolomite. In addition, iron and manganese oxides act as such in certain processes where their performing this function is uncontrollable, as is the case in the acid open hearth. Referring to limestone and dolomite as blast furnace materials, there is a difference of opinion among furnacemen as to their relative value as fluxes. Some hold that limestone is the better, while others maintain that dolomite gives as good, if not better results, their opinions usually being influenced by their training and by the extent of their experience with these materials. The presence of magnesium in limestone in small amounts has little effect, but as the content increases, it may lower the fusion point of the resultant slag by the formation of double salts. A high percentage (over 3%) of magnesia in blast furnace slag renders it undesirable for cement, but for concrete, ballast, etc., it is desirable, as it makes the slag harder. Aside from this objection, not one of much weight, the factor that governs the choice between limestone and dolomite is the cost per ton of available base.

Available Base: By available base is meant the amount of basic substance that remains in the raw flux after the acids of its own content are satisfied. Referring to the analysis of limestones on a succeeding page, Table 20, it is at once noticed that the total is not 100 per cent. The substance that is missing is carbon dioxide, which constitutes 44.0 per cent. of pure calcium carbonate, and, being evolved as a gas, is seldom determined in making an analysis. Using the Bessemer stone as an example and remembering that the iron and phosphorus are completely reduced in the

furnace, we have remaining SiO_2, 3.43%; Al_2O_3, .86%; CaO, 51.45%; MgO, 1.66%. If now, it is desired to produce a slag in which the combined weight of the bases (CaO+MgO) equals the silica and alumina (SiO_2+Al_2O_3) the available base=(51.45+1.66)—(3.43+.86)=48.82%. In a similar manner the basic stone will show 52.66 per cent. available base, if it be calculated on the same slag basis.

Limestone, which term also includes **dolomite,** belongs to the sedimentary class of rock-formation and is widely distributed. Immense deposits underlie most of the area drained by the Ohio and Mississippi rivers. The best of these deposits are of more ancient origin than our coal beds, belonging to the Mississippi, or early carboniferous, period and previous geological periods. Some limestone is formed by chemical precipitation, but the greatest portion of these natural deposits in all probability originated by the accumulation of the remains of minute sea animals. During succeeding periods these deposits were covered to a great depth. They were later made accessible by processes of uplifting and erosion which have exposed the strata in places.

Supply of Limestone: The main supply of limestone for Carnegie Steel Company comes from the Altoona, New Castle, Martinsburg and Butler County districts, while that for the furnaces in the Lake districts is obtained from a deposit near Rogers, Mich. In the Altoona and Martinsburg districts the beds have been folded and broken in the uplifting and lie at various angles, while in the other fields their position is horizontal or nearly so. In all the districts, the stone is carefully sized to eliminate large lumps and the fines. This sizing involves both crushing and screening, and, in some cases, the screening must be supplemented by washing. In all cases, great care is exercised to keep the stone as free from clay as possible, as this is one of the disturbing elements in uniform blast furnace operation.

Action of Limestone in Furnaces: In the blast furnace, limestone is not affected, excepting for the liberation of carbonic acid, until the lower levels and higher temperatures in the furnace are reached. In the smelting zone, or the regions just below, it combines with the gangue, forming slag, and also unites with varying amounts of sulphur depending upon the conditions of temperature and basicity of the slag. Ordinarily, about one-half ton of limestone is required in the production of one ton of pig iron. In the manufacture of steel, it plays the part of a purifying agent. Phosphorus, in particular, cannot be removed, commercially at least, without it. Stone with the lowest silica content is usually reserved for open hearth furnaces, that with the lowest phosphorus for furnaces making Bessemer pig iron, while stones with higher phosphorus content are used in furnaces making

iron for basic open hearths. An analysis typical of each of these grades is shown in the following table:

Table 20. Representative Analyses of the Three Different Grades of Limestone.

	Open Hearth	Bessemer Pig	Basic Pig
Silica	.80 %	3.43 %	1.20 %
Iron	.10 %	.30 %	.60 %
Phosphorus	.005%	.006%	.033%
Moisture	.10 %	.60 %	.60 %
Alumina	.16 %	.86 %	.70 %
Lime	54.90 %	51.45 %	53.88 %
Magnesia	.47 %	1.66 %	.68 %

Neutral Fluxes: For the purpose of making slags more fusible without changing their acidity or basicity, neutral substances having very low fusion points may be used. This practice is common in basic open hearths. Fluorspar is the substance generally used, though calcium chloride can be substituted.

SECTION II.

SLAGS.

Slag is the name applied to the fused product formed by the action of the flux upon the gangue of an ore and fuel, or upon the oxidized impurities in a metal. As previously indicated, it results from the neutralization of bases and acids, hence corresponds to the salts of wet chemistry. The word cinder is used interchangeably with slag, but cinder is also applied to refuse in a solid form.

Functions of Slags: On account of their fusibility, chemical activity, dissolving power, and low density, slags furnish the means by which the impurities are separated from the metal and removed from the furnace. Incidentally, they perform other important functions. Lying upon the molten metal, they serve as a blanket to protect it from the injurious action of hot gases, and being poor conductors, they prevent over heating of the metal and at the same time conserve its heat by preventing radiation. Since they possess the power of dissolving oxides, they mark a sharp line between reduced and unreduced material, and on this account serve to keep the metal clean.

Importance of Slags: In the metallurgy of iron, the importance of slags cannot be over emphasized. In the blast furnace they furnish the only positive means of removing sulphur, and, as their fusion temperature varies with their composition, they are one of the means by which hearth temperature is regulated. On this account, the slag controls to the greatest extent the quality of the iron produced. In the open hearth, particularly in the basic process, the slag is the only means by which the impurities

in pig iron, excepting carbon, are removed. To the metallurgist a knowledge of the properties of slags is essential. He understands their chemical behavior, knows their formation temperatures, fusibility and fluidity, and how to control these factors.

The Chemical Composition of Slags is within the control of the metallurgist, and by varying it, slags of almost any set of properties desired may be produced. Slags are mainly composed of two or more silicates in which other substances are dissolved or suspended. In the blast furnace, the slag will consist principally of calcium silicate, with a part of which the magnesium charged into the furnace will be found as a double salt. The same may also be the case with the small quantities of iron, manganese, and traces of alkali found in these slags. The sulphur removed will be in the form of CaS, which dissolves in this mixture. As to the state of alumina, which usually makes up 12 per cent. or more of the slag, there is room for doubt. By some it is considered as a base; by others, an acid. As noted under the heading of fluxes, it has the properties of both an acid and a base. Hence, being governed by the Law of Mass Action, it acts as a stabilizer to maintain a kind of equilibrium between acids and bases. In a highly silicious slag it may side with lime to form a double silicate, while in a strongly basic slag it takes the place of silica in neutralizing lime and magnesia. Since it has very weak properties in either direction, it seems reasonable to suppose that, in a case where lime and silica are in stable proportions, all or a part of the alumina may play a neutral part and dissolve in the slag. In ordinary blast furnace practice, however, the sum of the silica and alumina ($SiO_2+Al_2O_3$) is considered as the acid of the slag, while lime plus magnesia (CaO+MgO) is taken to represent the base.

Relation of Acids to Bases in Blast Furnace Slags: By chemical analysis of blast furnace slags it is found that, usually, $SiO_2+Al_2O_3$= about 48 per cent. of the slag, the ratio of SiO_2 to Al_2O_3 being about 2 : 1. After deducting from the lime enough to satisfy the sulphur, the sum of the remaining lime together with the magnesia (CaO+MgO) will also be about 48 per cent. This relation of acid to base will generally vary through a range of about 2 per cent., any increase in one being followed by a corresponding decrease in the other. The remaining 4 per cent. to 5 per cent. is made up of CaS and small amounts of ferrous and manganous oxides. As previously indicated, the ratio of lime to magnesia may vary somewhat without noticeably affecting the properties of the slag. The following results of an analysis represent a slag production by a furnace making basic iron.

Table 21. Showing Relation of Acids to Bases in Blast Furnace Slags.

Acids		Bases			
SiO_2	35.02%	CaO	44.03%	FeO	1.16%
Al_2O_3	14.99"	MgO	2.72"	MnO	1.08"
	50.01"		46.75"	S	1.35"

Ratio of Acids to Bases in Open Hearth Slags: Final basic open hearth slags contain a much higher percentage of bases than blast furnace slags and a much lower percentage of acids. The lime and magnesia will always be more than twice the silica, alumina and phosphorus. Some open hearth furnacemen hold that the best results are obtained when the percentage of lime plus magnesia in the final slag is three times that of the silica. The strong basic character of basic slags is necessary for the removal of phosphorus and the small and variable amounts of sulphur possible by the process. If the percentage of lime is too high, the slag will be viscous and retard the working of the heat. The following analysis is the average tapping slags from thirteen basic furnaces.

Table 22. Relation of Acids to Bases in Basic Slags.

Acids, per cent.		Bases, per cent.	
SiO_2	20.74	CaO	40.90
Al_2O_3	3.55	MgO	9.67
P_2O_5	2.85	FeO	10.84
S	.04	Fe_2O_3	5.24
SO_3	.23	MnO	5.86
	27.41		72.51

Acid to Base in Acid Furnaces: Both in the acid open hearth and in the acid Bessemer processes the slags will consist, practically, of the oxides of iron and manganese silicates. In both cases the silica, SiO_2, is usually about 50 per cent.; that in the acid open hearth is seldom higher than 52 per cent. or lower than 48 per cent., while acid converter slag will sometimes contain as high as 65 per cent. The remainder of about 50 per cent. will consist of FeO and MnO, together with small amounts of lime and magnesia and traces of phosphorus and sulphur. Acid open hearth slags are self regulating as to the amount of FeO and MnO. These oxides, in such slags, are always present in such quantities that their combined percentage is equal to about 46 per cent. of the slag.

Electric Steel Furnace Slags: The composition of these slags is affected by the kind of steel made and the method of refinement used. However, the final slag of an electric steel, that is, the slag formed near the end of the reducing period, should be very basic, very low in iron and manganese content and show a goodly percentage of calcium carbide. The following analysis may be considered as representing a good average finishing slag for this process:

Silica, 17.90%; Iron, .32%; Lime, 61.51%; Magnesia, 7.47%; Manganese, .35%; Sulphur, 1.30%; Calcium Carbide, .51%; Alumina, 6.00%.

Acids Formed by Silicon: A study of slags is facilitated by a study of the acids of silicon. There are a number of these acids which chemists consider as being derived from orthosilicic acid, H_4SiO_4 or $(H_2O)_2$ SiO_2,

through the loss of varying amounts of water, and are called polysilicic acids. When orthosilicic acid, $(H_2O)_2 \cdot SiO_2$, is set free from its salts, it always forms $H_2O \cdot SiO_2$, which is called, therefore, metasilicic acid or normal silicic acid. The relations of these various acids are shown in the following table:

Table 23. Acids Formed by Silicon.

Orthosilicic Acid	Metasilicic Acid	Polysilicic Acids	Water
$(H_2O)_2 \cdot SiO_2$	$H_2O \cdot SiO_2$		$+ H_2O$
$2(H_2O)_2SiO_2$		$(H_2O)_3 \cdot (SiO_2)_2$	$+ H_2O$
		$H_2O \cdot (SiO_2)_2$	$+ 3H_2O$
$3(H_2O)_2SiO_2$		$(H_2O)_4 \cdot (SiO_2)_3$	$+ 2H_2O$
		$(H_2O)_2 \cdot (SiO_2)_3$	$+ 4H_2O$
		$H_2O \cdot (SiO_2)_3$	$+ 5H_2O$

Besides these acids, salts of other acids, which do not fit into this table, are known to exist, such as $(H_2O)_4 \cdot SiO_2$. By substituting bases like CaO, MgO, FeO, MnO, for H_2O in these formulas, silicates such as are formed in slags would be represented. In the case of sesquioxides, as Fe_2O_3 and Al_2O_3, in which the valence of the metal is increased to three, this substitution cannot be made on a basis of 1 for 1, but 2 for 3, and the formulas are, therefore, more complicated.

So-called Acid and Basic Slags: In substituting a base, such as CaO, in the formulas above, it will be observed that the relation of base to silica varies in the different compounds through the wide range from 4 CaO combined with 1 SiO_2, $(CaO)_4 \cdot SiO_2$, to 1 CaO combined with 3 SiO_2, $CaO \cdot (SiO_2)_3$. The salts of the meta-and the ortho-acids, $(H_2O) \cdot SiO_2$ and $(H_2O)_2 \cdot SiO_2$, in which, for example, CaO is combined with 1 SiO_2, and 2 CaO with 1 SiO_2, appear to occupy positions of equilibrium or neutrality. Any increase of lime increases the affinity of the slag for acids, whilst a decrease in lime content causes the slag to exhibit acid properties. Slags of this composition are also very fusible and flow readily.

Classification of Slags: Some metallurgists classify and name the slags derived from the acids of silicon according to the ratio of oxygen in the base to oxygen in the acid, as shown in Table 24:

As illustrating the importance and value of this table, it is sufficient to say that it is often made the basis of calculation for the theoretical burdening of the blast furnace. These calculations are necessary in dealing with new and unfamiliar materials in order to determine the proper proportion of fuel, ore and flux in the charge. From the type of slag best suited to produce the kind of iron desired, the oxygen ratio is fixed upon, which in turn determines the relation of acids to bases. Then, with the analysis of the raw materials in hand, the impurities in each are

combined according to this relation. As a result of this combination the excess acids of fuel and ore are found, and the available base of the flux. These quantities, being combined in accordance with the slag ratio, will then, with the exception of variations in fuel consumption, fix the relations of the three materials.

Table 24. Method of Classifying Slags.

Monoxide Base	Sesquioxide Base	Oxygen in Base		Oxygen in Acid	Name	Fusibility
$(CaO)_4 \cdot SiO_2$	$(Al_2O_3)_4 \cdot (SiO_2)_3$	2	:	1	Subsilicate	Fusible
$(CaO)_2 \cdot SiO_2$	$(Al_2O_3)_2 \cdot (SiO_2)_3$	1	:	1	Monosilicate	Very Fusible
$(CaO)_4 \cdot (SiO_2)_3$	$(Al_2O_3)_4 \cdot (SiO_2)_9$	2	:	3	Sesquisilicate	Very Fusible
$CaO \cdot SiO_2$	$(Al_2O_3) \cdot (SiO_2)_3$	1	:	2	Bisilicate	Moderately
$(CaO)_2 \cdot (SiO_2)_3$	$(Al_2O_3)_2 \cdot (SiO_2)_9$	1	:	3	Trisilicate	Less Fusible

Uses of Slags: While to the metallurgist slags represent refuse no longer useful to his art, they may be applied to many purposes. Railroad ballast, road building, roof covering, concrete work, Portland cement, insulating materials, fertilizers, brick, and sand for mortar are some of the avenues open for the economic disposal of slags.

CHAPTER VI.

THE MANUFACTURE OF PIG IRON.

SECTION I.

SOME INTERESTING HISTORICAL FACTS.

Early History of Iron:[1] While the sole purpose of this chapter is to describe the manufacture of pig iron as carried on at the present time, one or two of the many interesting topics presented by the historical aspects of the subject will be found pertinent. A word as to the origin of the use of iron will serve to emphasize the process of evolution through which this wonderful industry has passed in attaining its present state of advanced development. When iron was first used, no one knows, for that date belongs to prehistoric times. Archaeological research can only establish that it has been in use by man through a period of about four thousand years. Evidence as to the extent of its use during the first three thousand years of this period is lacking, but it is very probable that the metal was used much more extensively than the few specimens uncovered would indicate. The corrosive properties of iron make it, to the archaeologist, a perishable substance that leaves no trail. If the use of iron on this continent were to cease suddenly today, no evidence of its present extensive application would be expected a thousand years hence. Therefore, only occasionally is some implement or ornament found among ancient ruins. There is doubtful evidence of its use by the Egyptians in building the pyramids, about 4000 B. C. As to its use by the ancient Hebrews, by the Assyrians about 1400 B. C., and, more recently, by the Greeks, there can be no doubt. The Greeks were followed by the Romans who became somewhat proficient in its metallurgy. These people, through their numerous and extensive conquests, the success of which they no doubt owed to the use of metals in making their instruments of war, spread the art of extracting and fashioning it throughout Europe. Some knowledge of the metal, however, preceded them, for Caesar, crossing the English Channel, found it in use among the native Britons. During the Roman occupation, the industry grew to one of importance in England. At that time it was obtained by heating a mixture of ore and charcoal, probably in a flat bottom furnace or forge, until there had collected a small body of pasty metal which was then drawn and worked by hammering to make wrought iron. Such, briefly, was the process until 1350, when the iron makers of Central Europe succeeded in producing iron that would melt in the furnace and permit of casting. This result they accomplished in a new type of furnace, built of masonry, which enclosed a shaft or vertical opening in the form of two truncated cones placed

[1] See Metallurgy of Iron by Thomas Turner, published by Charles Griffin and Co. Ltd., London.

end to end,—in a crude way, the lines of the modern blast furnace. The lower frustum came to be known as the boshes, the bottom, as the hearth. In this furnace, ore, flux and charcoal were charged in at the top of the furnace, while air, under very low pressure, was blown in at the bottom. This method was introduced into England about the year 1500 where, in 1619, coke was first used, to be followed, 200 years or more later, by the introduction of hot blast. In America the first iron works was established in Virginia on the James River in 1619, and about 100 years later (1710-1715) the first furnace using blast was built. Thence the industry spread, for the most part, westward.

Old American Furnaces: The furnaces of a period as recent as one hundred years ago were what would now be called very crude affairs. Portions of some of them are still standing, and one is within a two-hour ride of Pittsburgh. They were usually in the form of a truncated pyramid, twenty to thirty feet high, and constructed of stone work which enclosed a circular shaft, some four feet in diameter at the top and about eight feet at the bosh. The hearth was either round or square in cross section. The capacity ranged from one to six tons a day. By the year 1880, this output had been gradually increased to nearly 100 tons per day, with a daily coke consumption of nearly 300 tons. With all the basic principles in use for so long a time, it is remarkable that so little progress was made. About 1880, for reasons which would be too lengthy to explain here, very rapid advancement was made, so that now there are furnaces whose daily output of pig iron exceeds 600 tons with a fuel consumption of less than 2000 pounds of coke per ton of iron produced. Attention has been called to these facts here, because it is well to remember, in beginning the study of the modern blast furnace, that the present method for the extraction of iron from its ores represents a pyrochemical process just attaining its highest state of development.

The Importance of Iron: This topic needs no comment here. Pig iron, besides being used directly in the form of castings, is the intermediate from which all ferrous products are derived. Its importance is emphasized by the reports of the yearly productions.

SECTION II.

COMPOSITION AND CONSTITUTION OF PIG IRON.

Constitution of Pig Iron: In the solid form, pig iron represents a very complex mixture made up of uncombined elements, chemical compounds and alloys. The amounts and relations of these constituents may vary with conditions, so that the complexity of the mixture does not depend wholly upon the number of elements present nor upon their amounts. Initial temperature and rate of cooling are two of the most important factors affecting the properties of pig iron. These matters are of great importance when the iron is to be used for castings, and to understand them fully requires a very extended study of the subject. This chapter has to do mainly with pig iron as an intermediate product in the making of steel, so it will be most profitable to discuss only the subject of its composition very briefly.

Chemical Elements in Pig Iron: In addition to iron, the elements commonly occurring in pig iron are carbon, silicon, manganese, sulphur and phosphorus. Of these elements iron will constitute 91 to 94%; carbon, 3.0 to 4.0%; silicon, .50 to 3.00%; manganese, .25 to 2.50%; sulphur, less than .065%; and phosphorus .040% to 2.00% of the whole.

Carbon occurs in pig iron in two forms, called **graphitic carbon** and **combined carbon.** Graphitic carbon is practically pure carbon, existing in the iron in the form of tiny flakes which are distributed throughout the mass. It forms in the pig iron during the process of cooling, because the absorbing power of iron for carbon decreases as its temperature falls. Carbon in this form gives to pig iron the grayish black appearance so often seen. But in cooling, some of the carbon continues in combination with the iron as a definite compound, Fe_3C, 93.33 per cent. Fe and 6.67 per cent. C. Both forms of carbon produce marked effects upon the properties of the iron. The tendency of the graphitic is to weaken, while the combined carbon, up to the limit of about .90 per cent., strengthens it. In Metallography the compound Fe_3C is called **Cementite,** and to the uncombined iron is given the term **Ferrite.** In cooling these two substances conduct themselves in a peculiar way toward each other. In passing a certain temperature (about 700° C.) they arrange themselves in layers in the definite amounts of approximately seven parts ferrite to one part cementite. The resultant stratified segregate will, therefore, contain approximately .85 per cent. of carbon. Under the microscope these stratifications present the appearance of mother of pearl, whence it is named **Pearlite.** Pearlite is the strongest constituent of cast iron. When heated, iron absorbs carbon, and from the fusion point this absorption becomes very rapid. The limit, called the saturation point, beyond which it will not absorb any more, varies with the temperature, and is also affected by the amount of silicon present, a rise in the percentage of silicon causing a corresponding decline in the carbon content. Silicon tends, also, to decrease the combined carbon, and increase the graphitic. Manganese and chromium have the opposite effect. Rapid cooling tends to prevent the formation of pearlite and graphite. In general, the more rapid the cooling the less the graphitic carbon and the greate the combined carbon content will be.

Silicon: In small quantities silicon has little direct effect on pig iron, but an increase above 4 per cent. makes the iron very brittle, hence foundry iron will seldom contain more than 3 per cent. In iron for basic open hearth use the percentage of silicon should not be higher than 1.25, as a high silicon content tends to flux away the lining of basic furnaces very rapidly. For the acid Bessemer process, iron containing about 1.25 per cent. silicon is desirable, but the content may vary from 1.00 per cent. to 1.50 per cent. The oxidation of the silicon in the Bessemer process produces a large quantity of heat, so that iron containing a high percentage of this element is usually referred to as hot iron. The amount reduced

in the blast furnace is variable and depends on conditions of slag and temperature. Its effect on the carbon has just been noted. Since it tends to throw the carbon out of solution, silicon is used to regulate the depth of chill in chilled castings. A content of one per cent. silicon in ordinary low sulphur iron renders it difficult to obtain a chill. Below this percentage the chilling properties of the iron are, roughly stated, in inverse ratio to the amount of silicon present.[1] Silicon also prevents blow holes, and tends to decrease the shrinkage in white irons.

Manganese alloys with iron in all proportions. An alloy containing 10 to 25 per cent. manganese is called spiegel. Alloys containing 40 to 80 per cent. manganese are called ferro-manganese. Up to one per cent., manganese tends to strengthen pig iron. It decreases the bad effects of sulphur, with which it combines, replacing iron. Its presence opposes that of sulphur, so that, with uniform raw materials, furnace conditions that give a high percentage of manganese tend to decrease the percentage of sulphur. Hence, in reasonable amounts of about one per cent, it is desirable, especially for basic open hearth use, where it also aids in the elimination of sulphur. In Bessemer practice iron with a manganese content of about .50 per cent. is desirable. The element is oxidized, and unites with silica to form a slag that fuses at a comparatively low temperature and is very fluid, so that iron containing a higher percentage than that indicated by the latter figure gives rise to a condition in blowing known as a "sloppy" heat. As to whether manganese has a good or a bad effect on cast iron, there is much difference of opinion, some considering it almost as a cure for all troubles and others condemning it as a source of much trouble, especially in chilled castings. While it tends to hold carbon in solution, chill produced by increasing the manganese content alone is soft and tends to spall.[1] In moderate amounts it is said to prevent cracking of the surface and also spalling to some extent, especially in chilled rolls. From 50 to 75 per cent. of the total amount of manganese charged into a blast furnace making pig iron is obtained with the metal.

Sulphur in pig iron is generally supposed to be injurious, though recently the statement that the inferior qualities exhibited by high sulphur iron are due entirely to its presence has been questioned. Nevertheless, as sulphur in steel is considered undesirable and as the blast furnace affords the only positive means of reducing it, pig iron containing less than .05 per cent. is desirable for making steel by all the fusion processes. Sulphur with iron forms iron sulphide, which is soluble in the metal and has a melting point that is lower than the other constituents of the iron. According to some authorities[1], this sulphide in iron used for castings has a three-fold influence. First, it tends to hold the carbon in combined condition, hence can be used to increase the depth of chill in chilled castings; second, its low melting point causes it to segregate as the iron solidifies, thereby causing the condition in castings known as bleeding; third, it

[1]See The Principles, Operation and Products of the Blast Furnace, by J. E. Johnson, Jr. Published by McGraw-Hill Book Company Inc., New York.

increases the shrinkage of the iron to a marked degree, thus increasing the difficulty of making accurate castings and increasing the tendency to cracks which are a result of the high shrinkage. The chill imparted by sulphur is a very hard one, but is very brittle and somewhat unreliable.

Phosphorus is the only element entering the blast furnace over which the skill of the furnaceman has absolutely no control. Its compounds are completely reduced, so that all the phosphorus in the raw materials is found in the metal. Therefore, its content must be regulated by proper selection of raw materials. High phosphorus causes a slight brittleness in pig iron, and has a marked effect upon the total carbon. Ferro-phosphorus containing about 15 per cent. phosphorus is carbonless. Lesser amounts permit a proportionate increase of carbon, so that the total carbon in an iron containing .2 per cent. phosphorus may be as high as 4 per cent. In this respect its action is not selective, since the ratio of combined to graphitic carbon is not affected. Phosphorus is known to form a compound, Fe_3P, with iron, but it is able apparently to combine with it in several proportions. Ferro-phosphorus containing as much as 25 per cent. phosphorus is now manufactured. In iron for casting, phosphorus exercises a beneficient effect. It tends to eliminate blow holes, decreases shrinkage, and increases the fluidity. Above .5 per cent. it begins to weaken iron, so the amount used will be governed by the use to which the casting is to be applied.

Grading Pig Iron: Pig Iron is graded by chemical analysis. There are several systems employed, many of which are somewhat elaborate. The following table, which includes other important blast furnace products as well as ordinary pig iron, shows one of the simplest methods of classification:

Table 25. The Metallic Products of the Blast Furnace.

GRADE	RANGE IN PERCENT. OF				
	Silicon	Sulphur	Phosphorus	Manganese	Total Carbon
No. 1 Foundry.....	2.5 to 3.0	Under .036	.25 to 1.00	Under 1.00	3.50—4.25
No. 2 Foundry.....	2.0 to 2.5	" .045	.25 to 1.00	" 1.00	3.50—4.25
No. 3 Foundry.....	1.5 to 2.0	" .060	.25 to 1.00	" 1.00	3.50—4.25
Malleable Casting...	1.00 to 2.00	" .050	.2	" 1.00	3.50—4.25
Forge.....	About 1.50	" .100	1.0	" 1.00	3.50—4.25
Acid Bessemer.....	1.00 to 1.50	" .050	0.1 or less	About .50	3.50—4.25
Basic Bessemer.....	Under 1.00	" .050	2.00 to 3.0	Under .50	3.50—4.25
Low Phos. Acid Iron	" 2.00	" .030	.030	" 1.00	3.50—4.25
Basic.....	" 1.25	" .050	.100 to 1.00	1.00 to 2.50	3.50—4.25
Spiegel.....	About 1.00	" .050	.150	18.0—22.0	5.0 —6.00
Ferro-Manganese,...	.50 to 1.00	" .030	.10 to .30	78.0—82.0	5.0 —7.00
Ferro-Silicon.....	8.0 to 15.00	" .070	.10 to .50	.....	1.00—2.00
Silico-Spiegel.....	8.0 to 15.00	" .010	.15	15.00–20.00	.....

SECTION III.

A BRIEF OUTLINE OF THE PROCESS AND EQUIPMENT FOR THE MANUFACTURE OF PIG IRON.

Trend of Modern Improvements: With the preceding brief summary of the history, importance, and composition of pig iron in mind, the process by which it is manufactured furnishes a theme of great interest. Apropos of this idea, however, it is to be observed that a description of the modern methods of manufacture is rendered difficult both by the complexity of the details of the process and by its recent rapid development. As already pointed out, the fundamental principles have remained unchanged since the founding of the process, because experience has demonstrated that this process is the most practical. All improvements, then, have been made with the aim of increasing the production and at the same time decreasing the cost. These objects have been attained to a degree almost approaching perfection by the use of materials of greatest purity, selected through chemical control, by increasing the size of furnaces, by economies in fuel consumption, and by improved methods of handling the materials. The result is that the small plants of 100 years ago have been succeeded by complex and gigantic affairs. As the greatest changes have been brought about since 1880, a comparatively recent date, the blast furnace plant is just approaching the uniformity of perfection. Furthermore, since the improvements have been contributed by a great number of men, it is not to be wondered at that an inspection of the industry will reveal not only different stages of development but also many different methods of attaining the same end. The aims and fundamental principles being the same, however, the numerous plants, while differing greatly in detail, will present certain similarities in their gross features which may profitably be reviewed before proceeding with the detailed description.

Essentials of the Process: Essentially, the present process for the extraction of iron from its ores consists in charging a mixture of ore, fuel, and flux in proper proportions through a specially constructed opening in the top of a tall cylindrically shaped furnace called a blast furnace, while heated air is simultaneously blown in near the bottom through openings, called tuyeres, the nitrogen of the air together with the products of combustion and reduction passing upward and escaping through openings at the top. These parts of the process, being almost continuous ones, are accompanied by the periodic removal of a part of the impurities in the form of slag at an opening between the tuyeres and the bottom, and by a like removal of metal through a larger opening at the bottom. In order to carry out these operations on the large scale previously mentioned, it is evident that extensive equipment is required.

Essential Equipment: The central feature in this equipment is the furnace, which is provided with apparatus for hoisting the materials to the top and with ladles for containing slag and molten metal, to which is some-

times added casting beds or pig machines for casting the metal into "pigs" of convenient size, and slag granulating pits. Next in importance follows the blowing engines for producing the blast, then the stoves for heating it. Of great importance is the pumping station, the function of which is to furnish the great quantities of water needed for steam, for cooling, etc. As the gases that escape from the top of the furnace are combustible, apparatus for their most efficient disposal is desirable. They are used to heat the stoves and to generate power either by burning them under boilers or in gas engines, in which case they must be cleaned of the large quantities of flue dust which they carry out of the furnace. As the moisture in the air affects the efficiency of the furnace, some modern plants will be provided with apparatus for drying the blast. Referring again to the solid materials of the charge, modern equipment requires a stock house, topped by bins, in which the ore, fuel and flux may be temporarily stored and conveniently removed for weighing or measuring before delivering it to the hoisting device. Adjacent to the bins will be located the stock yard containing the ore pile, which is spanned by the ore bridges. A car dumper, advantageously situated, will complete this part of the equipment. Finally, the various parts of the plant will be made accessible by a system of railways for transporting the materials.

SECTION IV.

CONSTRUCTION OF THE BLAST FURNACE PROPER.

The Gross Features of the Furnace Proper: The modern blast furnace is a tall circular structure, 90 to 100 feet high, built of fire brick, reinforced externally by a close fitting steel shell and encasing internally a circular space of varying diameters. This space is divided into three main parts. The bottom section, called the hearth or crucible, is cylindrical in form and some 10 to 12 feet deep in the larger furnaces. The second section, having an altitude of some 12 or 13 feet, is called the bosh. It is in the form of a frustum of a cone, which, in an inverted position, tops the crucible with its smaller base. Setting above the bosh in an upright position with an altitude of about 70 feet, is the stack. Formerly its outline was also that of a frustum of a cone, but recent studies of furnace lines indicate that the slanting lines of the cone should be changed to the vertical for a distance of 4 or 5 feet above the bosh, and for about 10 feet from the lower bell at the top. The whole is now capped by the furnace top, which completes the list of the gross features of the furnace proper.

The Foundation: Before proceeding with the details of the parts noted above, the foundation should be considered. In view of the immense weight which it is required to support, this part of the furnace is of great importance, because any extensive settling of the furnace after it is in operation would result in serious troubles and probably put it out of commission. The depth of the foundation will vary with the conditions of the

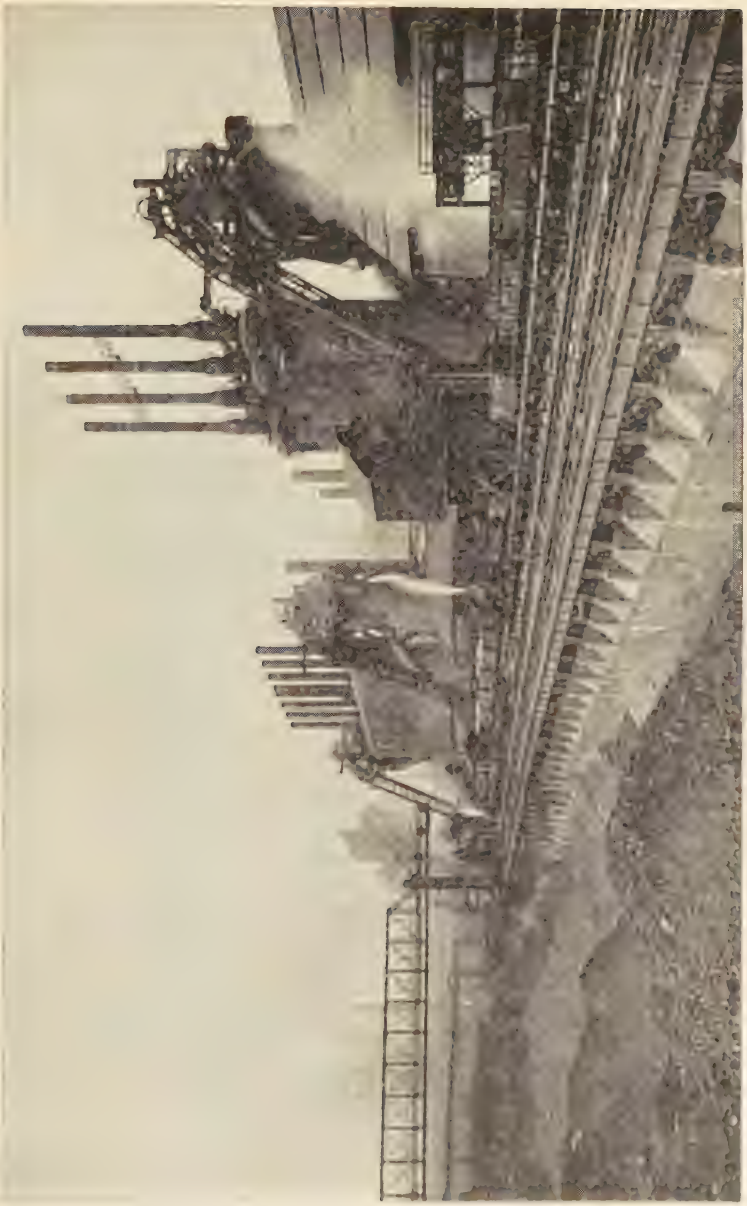


FIG. 44. View, from Charging Side, of Part of a Blast Furnace Plant.

rock materials on which it is to stand. If these be sand or clay, it may be necessary to drive piling for a depth of many feet, and upon this begin the foundation. On the other hand, if solid and firm rock underlies the location for the furnace, an excavation to this rock is all that is required. A proper bed having been found or otherwise provided, the foundation is started and built up several feet with concrete, which extends some distance outward beyond the floor of the furnace. The remainder of the foundation is then made up of common brick of good quality and strength, except the space directly beneath the hearth and walls of the furnace, where firebricks are used.

The Hearth or Crucible is the portion of the furnace which serves as a receptacle for the molten metal and slag. It is constructed of fire brick of the best quality; its wall is usually sixty inches or more in thickness; and it may be protected in places with water cooled plates, if the furnace is of recent construction. At the bottom the walls of the hearth are usually stepped out into the interior of the hearth for four or five courses of brick. This construction gives the bottom surface a slight basin shape, and tends to hold the bottom brick in place. The hearth varies in diameter and depth with the size and capacity of the furnace. In the larger ones, it is about eighteen feet in diameter and eleven feet deep. Externally, it is reinforced by a heavy metal jacket made of steel plates that are riveted together, or of iron castings in segments that are jointed and bolted together. Jackets are always cooled, those of cast iron by internal circulating systems, and those of steel by coolers set between the brick work and the jacket. The upper diameter of this jacket is smaller than the diameter at the base, so that the jacket will better hold the walls of the hearth in place by offering resistance in opposition to the buoyant forces of the bath and slag.

The Bottom of the crucible is built of fire brick, sometimes in the form of large blocks, which are laid on end with closely fitting joints in order to prevent intrusion of metal. Bottoms vary in thickness from about six feet in the smaller furnaces to about twelve feet in the large ones. The bricks are almost entirely replaced in time by metal, which, collecting in a solid mass, often weighing many tons, is known as the **salamander.**

Tapping Hole: Situated at some convenient point in the circumference of the hearth and just above the top course of stepped-in brick is the **tapping hole,** or **iron notch.** If the bricks are not stepped-in, the opening will be at the bottom. It may be a square opening in the brick about 8x8 inches or an oblong or rectangular one 6x8 inches on the inside. The outside dimensions may be somewhat larger to permit of easily inserting the tapping tools. Proper provision is made for the protection of the hearth jacket at this point with a water cooled plate, called the dam plate. During the tapping of iron, the metal structures directly above the tapping hole are protected with a **splasher.**

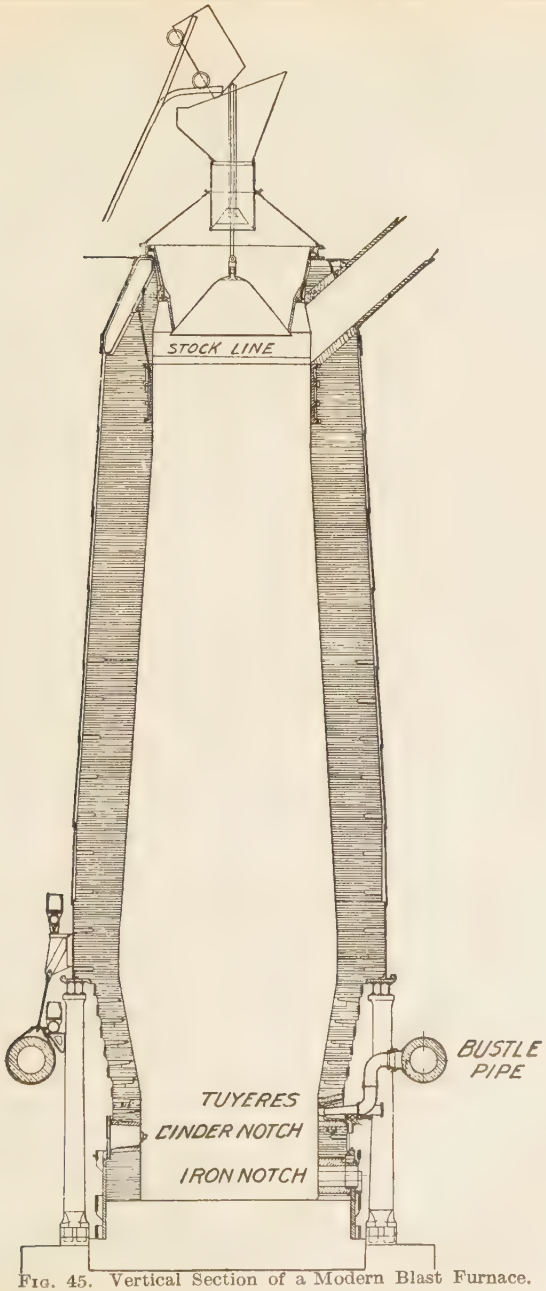


FIG. 45. Vertical Section of a Modern Blast Furnace.

Cinder Notches: There is usually but one cinder notch. This opening may be placed at any convenient point in the circumference of the hearth at a sufficient height above the tapping hole to permit the collection of the desired amount of iron between tappings. In the larger furnaces it is about six feet from the floor of the hearth and four to five feet above the tapping hole, being generally placed 45° or 90° from this opening. Unlike the tapping hole, this opening is water cooled to protect the brick from the fluxing action of the slag. Hence, the opening in the brick work is larger, being about one foot in diameter inside and increasing to about two feet on the outside. In this circular cone-shaped hole in the brick the cooling devices are placed. These are castings, usually made of copper, and consist of a **cinder cooler,** an **intermediate,** or **monkey, cooler,** and a **monkey.** The cinder cooler is in the form of a hollow frustum of a cone. It is about two inches thick, and, between its walls, proper provision is made for the circulation of water. It is made to fit the hole in the brick work and is tamped securely in place with fire clay. The opening in this cooler is then reduced by inserting into its inner end the close-fitting intermediate cooler, which is constructed like the cinder cooler, but smaller and shorter. Finally, the still smaller monkey, through which water circulates also, is inserted, reducing the opening to about two inches. A short iron rod, called a **bott,** tapered to fit the monkey and attached to a long steel rod which serves as a handle, was formerly used to close the opening, but recently these hand botts have been replaced on many furnaces with mechanical botts that may be operated from a distance. The sizes of the three coolers are regulated so that the large diameters of the monkey and intermediate cooler fit the smaller diameters of the intermediate and cinder coolers, respectively. Thus, the monkey, when in position, is wholly within the furnace. In each of these castings and within their topmost quadrant, when in position for service, are provided two threaded holes into which the pipes for ingress and egress of the cooling water may be inserted.

Tuyeres: The tuyeres, from ten to sixteen in number, are distributed symmetrically about the upper circumference of the hearth just below the boshes. Their function is to provide passages for the blast. They also determine the height to which the slag in the furnace may rise. In the large furnaces, this height is about three feet. Fitted into the opening in the brick, flush with the wall, both internally and externally, is the **tuyere cooler.** It is similar to the cinder cooler, and set tight with fire clay. The tuyere itself, of copper, presents an internal diameter of from four to seven inches, while its external diameter is such as to permit it to fit snugly into the smaller end, or nose, of the cooler and project several inches into the furnace. Like the cooler, the tuyere is water cooled and is tapped at two places in the top quadrant for the insertion of water pipes through which a copious stream of water must be kept flowing to avoid burning it.

Tuyere Connections: With one end fitting closely against the tuyere, is a horizontal cast iron pipe, about five feet long, called the **blow pipe,**

sometimes the "belly" pipe. Through it the hot blast is delivered to the tuyere from the **tuyere stock,** to which the names **leg pipe, boot leg** and **pen stock** are also often applied. The blow pipe may be slightly larger in diameter at one end than at the other, and both ends are turned to fit into slight sockets in the tuyere and the tuyere stock. It is held in place with the smaller end fitting into the tuyere by pressure from the **tuyere stock,** which is provided with a spiral spring and connecting rod, attached to the hearth jacket, for this purpose. The tuyere stock curves upward immediately on leaving the blow pipe, and a hole in a lug on its under part gives an opening through which the connecting rod passes through the coiled spring to the hearth jacket where it is anchored. The heavy spiral spring, which provides pressure and at the same time allows motion due to expansion and contraction of the tuyere stock and blow pipe with changes in blast temperatures, is placed between this lug and a large brass nut on the other end of the connecting rod. The nut is made of brass so it will not rust and be difficult to operate. In the outer part of the curve in the tuyere stock, and in the center line of the blow pipe and tuyere is a small opening, closed by the **tuyere cap** or "wicket," through which a small rod may be inserted to clean out the tuyere without removing the blow pipe. The wicket must be of such a form that it may be opened readily at any time and still be practically gas tight. To meet these conditions the wicket is constructed on the principle of the ball and socket joint. The ball is attached to the end of the short arm of a right angle lever and is held tightly in the socket by a ball weight attached to the long arm. A smaller opening, called the peep hole, in the tuyere cap is covered with glass, which permits inspection of that portion of the interior of the furnace directly in front of the tuyeres. Extending upward, the tuyere stock connects with the nozzle of the **goose neck,** to which it is clamped by means of lugs and keys that fit into seats of hanging bars. The goose neck then turns at right angles and extends horizontally to the **neck** of the **bustle pipe** to which it is fitted and securely fastened by flanges and bolts; or the tuyere stock may lead at an angle to the horizontal directly to the lower part of the bustle pipe. The **bustle pipe** is the large pipe, about four feet in outside diameter, which encircles the furnace and distributes the hot blast to the tuyeres. All these pipes, down to the blow pipe, are lined with fire brick. The bustle pipe is fed by the **hot blast main** which terminates at the stoves. It is of about the same size as the bustle pipe and lined with nine to twelve inches of fire brick.

Boshes: As previously described the bosh is that part of the furnace, just over the hearth, where the greatest diameter is attained. No shell or jacket covers the exterior of the bosh. A standard bosh is constructed in the following manner: Starting at the top of the hearth, the brick work, 30 inches in thickness, is stepped outward, externally, nearly six inches for each twelve inches of vertical rise. Each step-out is supported by means of a heavy steel band, or a pair of bands, called **bosh bands.**

Inserted in the walls of the boshes, through cast iron "boxes," placed in the brick spaces between pairs of bosh bands, will be found cooling plates, called the **bosh plates,** in horizontal rows about two feet apart, measuring vertically. The plates in each row will be about four or five inches apart, and the plates in the different rows will be staggered vertically, breaking joints like brick work. This construction adds to the cooling efficiency of the plates. There are several different makes of bosh plates, but the more common ones will be somewhat wedge-shaped, with a flat bottom and oval top, and about four inches thick at the point of their greatest altitude. They are hollow and have inserted in them, usually at opposite corners, two pipes through which water flows continuously. These plates are necessary to help protect the brick work, for, being just above the tuyeres in the zone of fusion, the bricks here receive the highest heat of the furnace. Formerly, the plates extended almost through the wall in new work, usually to within one course of brick, but it was found that this course of brick is soon cut away after the furnace is blown in, so now the plates extend entirely through the wall from the first.

Mantle: At the upper limits of the bosh is found the **mantle,** conforming to the shape of the furnace at that point and totally encircling it. The mantle is made up of heavy steel plates and angles, upon which rests the weight of the stack. It is supported by a series of cast iron pillars or fabricated steel structures, which rest on foundations supported by the main furnace foundation. This construction allows the entire bosh and hearth to be removed without disturbing the rest of the furnace.

Shaft, or Stack, and Inwalls: The shaft comprises all that part of the furnace which is located above the boshes. The wall of this shaft is usually, in an imaginary way, divided into three almost equal parts, called the upper, middle and lower inwalls. Up to this point, the construction for all furnaces is fairly uniform as to general features. But as to the inwalls three types are employed, namely, the thick, the intermediate, and the thin wall. The construction necessarily differs for these different types. Therefore, each type is best described separately.

Thick Wall Type: The inwalls of this type are about five feet thick, and are inclosed in a heavy riveted steel shell about one-half inch thick. The shell is usually made oversize to provide a small space between it and the brick work, in which space is tamped lightly a packing of loam and granulated slag, to allow for the expansion and contraction of the inwalls. Thick walled furnaces are seldom water cooled above the bosh, and their walls furnish the sole support for the top. In case their walls are cooled, this is done by means of cooling plates inserted as shown in Figs. 45 and 46.

The Furnace Lines and Bosh Angles of furnaces of the thick wall type differ somewhat. In modern blast furnace construction the lines of

the furnace, by which is meant the lines formed by the inner edges of a vertical section through the center, with their enclosed angles, are considered of great importance. In the old furnaces, the lines of the inwalls were straight, and the boshes somewhat flat with corresponding sharp angles. But with the fine ores from the Lake Superior district, experience has taught that much better practice is obtained with more nearly vertical lines. So, in the latest type of furnace, the lower inwall will rise vertically for several feet, the boshes will be steep, and the upper inwall will drop vertically for a distance of about ten feet from the stock line. Bosh angles, that is, the angles at the top of the bosh, which its wall forms with a horizontal from the center of the furnace, are now being increased from about 75° to 80°. These steeper boshes are proving to be an important improvement.

Intermediate, or Semi-Thin, Wall Type: In the intermediate type, the walls are about three feet thick, and to protect the brick as much as possible, cooling plates, similar to bosh plates, are inserted in the lower inwall. They may extend for a distance of from twenty to forty feet above the bosh. The top in this type is sometimes supported by columns of fabricated steel, but in the majority of cases it is supported by the walls as in the thick walled type. The inwalls are surrounded by a steel jacket as in the thicker type, the only difference being in the necessary openings for the coolers.

Thin Walled Type: In this type the inwalls are from nine to eighteen inches thick, the top is always supported by structural work, and the shell must be cooled throughout its entire length. This cooling may be done in three ways. One method consists in spraying the jacket with water, conducted through suitably arranged pipes and enclosed by a light "splash jacket" which conforms to the size and shape of the stack. In the second method the shell is encircled by a series of deep and narrow horizontal troughs through which water is kept flowing from the top to the bottom of the furnace, overflowing from each trough to the next succeeding lower one. Each of three or four of these troughs drain separately to a common point where the temperature of the water can be noted. In the third type, the entire outer surface of the stack is kept covered with water by means of a spiral trough which, slightly separated from it, encircles the stack from top to bottom. This trough is kept full of water by a series of feed lines that enter it at various points in the spiral. At present very few furnaces of this type are being built.

Furnace Linings: The brick-work which forms the hearth, bosh and inwalls of a furnace are referred to as its linings. All the brick used in the construction of these parts are made of fire clay, and are of three kinds, known as **hearth and bosh brick, inwall brick** and **top brick,** each of which is made of such materials and in such a way as to render it best adapted to the conditions it is to be subjected to in service. The hearth and bosh brick are required to resist a very high temperature and the action of flux

and slag; inwall brick must be able to withstand abrasion at a moderately high temperature; and top brick, always at a comparatively low temperature, must resist the impact and abrasive forces of the charges as they are dropped into the furnace. These different qualities in the different bricks are obtained by varying the method of manufacture especially with respect to composition, degree of grinding and temperature of burning. As to the former factor, three classes of materials, or clays, are available. These are flint clay, plastic clay and calcined clays. Mixtures employed by different manufacturers are by no means uniform, but the following may be taken as fairly representative of good practice.

Table 26. Showing Data Relative to Fire Brick for Use in Blast Furnaces.

Kind of Brick	PROPORTION OF				
	Flint Clay	Calcined Clay	Plastic Clay	Manner of Grinding	Final Temperature of Burning
Hearth and Bosh Brick	50 to 65%	20 to 35%	14 to 16%	Coarse	1350°C
Inwall Brick	40%	30 to 40%	20 to 30%	Medium	to
Top Brick..	0 to 30%	30 to 50%	40 to 50%	Fine	1450°C

All the materials, irrespective of the kind of brick, should be and are of the best quality obtainable, and the brick are carefully inspected before being put in place in the furnace. The three kinds of brick are distinctly marked by the manufacturer, so that the danger of wrongly placing a brick, a top brick in the hearth, for example, may be avoided. Great care is exercised with respect to brick, because the life of the furnace depends in a large measure upon the lining, and the item of cost for brick is not a small one. In the construction of one of the large modern furnaces, close to the equivalent of 800,000 nine-inch brick are required, and the average consumption of brick is a little more than two brick for each and every ton of pig iron produced. Fire bricks are always laid in a thin slurry composed of fire clay and water. The slurry is applied by pouring it on the top of each course with a dipper, and is followed immediately by the next course of bricks, which are hammered into place to squeeze out all the fire clay except that required to compensate the inequalities of the brick.

Water Trough: Encircling the furnace bosh, inside of and above the bustle pipe, will be found one or more water troughs into which the water supplying the numerous cooling plates is discharged in visible streams, thus providing means of determining when a plate is burned out. The water, flowing from these troughs into a well, may be pumped back through the cooling system, and thus be used over and over.

Tops: At the present time furnace tops are somewhat complicated affairs. In olden times the tops of furnaces were left open, the escaping gases being allowed to burn in the air. In the year 1814, these waste gases began to be employed in France for the purpose of burning bricks and heating small furnaces. The first attempt to heat the blast by utilizing these gases was made in 1834, and consisted in laying, across the tunnel head, pipes through which the air blast passed in going to the tuyeres. It was not till 1845 that a plan was evolved by which the gases could be used to heat the stoves. To effect this purpose, changes in top construction were necessary. At first the gases were merely drawn off by the chimney draft of the stoves through openings below the stock line. The arrangement, known as the **bell-and-hopper,** or **cup-and-cone**, was not put into use till 1850. It consisted in closing the top of the furnace by means of a large circular hopper, the smaller opening of which was closed by the **bell** that could be lowered and raised at will. With the bell raised against the hopper, the materials were dumped into the hopper; then the bell was lowered, and the charge dropped into the furnace. As large quantities of gas escaped with each lowering of the bell, this device was improved by the **double-bell-and-hopper,** which is of comparatively recent origin. Essentially, this improvement consisted in placing a second but smaller bell-and-hopper above the first, and providing a gas tight space of large size between the two. The raw material, upon being hoisted to the top, is first dropped or dumped into the upper hopper, whence it may fall into the larger hopper below when the small bell is lowered. The small bell being raised against the upper hopper, the large bell is lowered, and the charge falls into the furnace without the escape of gas. The bells are made of cast steel, in one piece, and of such a slope, 45° to 55°, as to permit the charge to slide off readily. They are usually supported from their top centers by means of a rod and a sleeve, each attached to a counterbalanced lever operated by means of a steam or air cylinder or an electric motor, controlled from the ground. The large bell is attached to the rod and the small bell to the sleeve. The hoppers, of cast steel or iron, will generally be made up in sections, which are securely bolted together. They are provided with a removable, but gas-tight, flange and extension ring, also in sections, which permit the bell to be readily removed in case a change is necessary. The details of this construction differ somewhat to conform to the introduction of improvements, with the type of hoist, and with the ideas of the different builders.

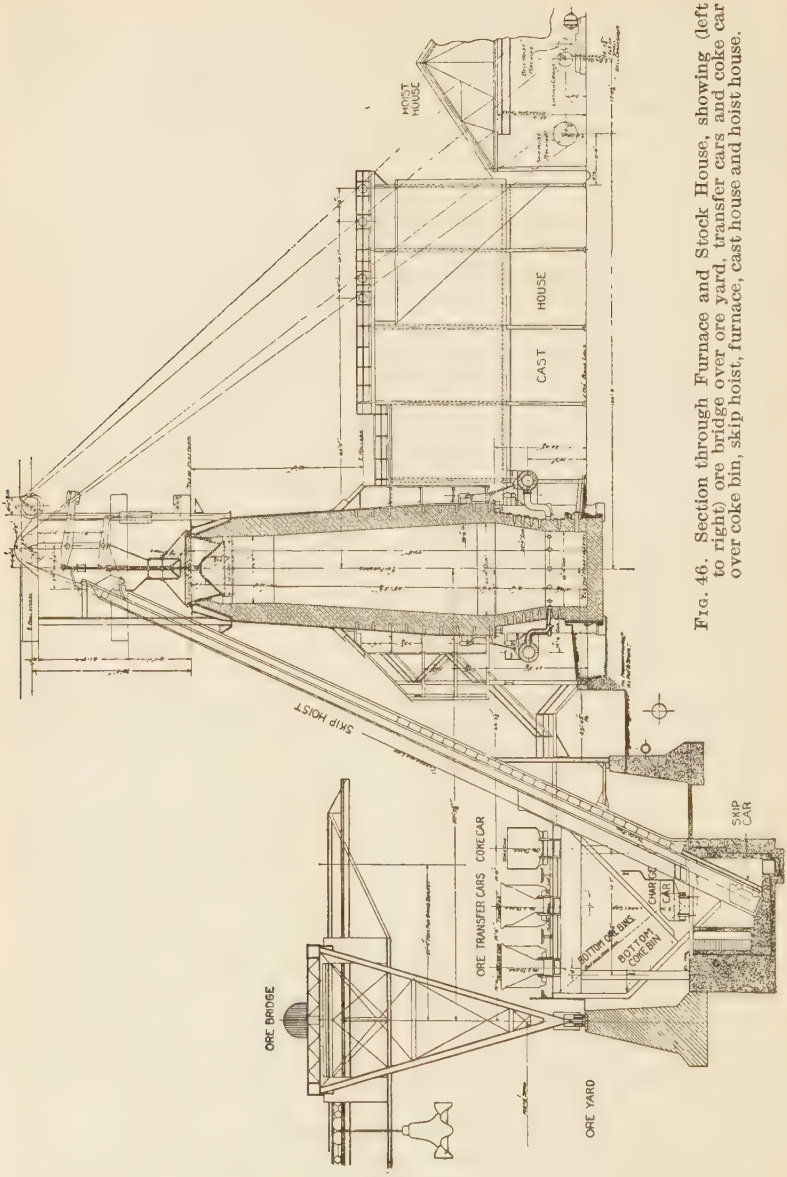


FIG. 46. Section through Furnace and Stock House, showing (left to right) ore bridge over ore yard, transfer cars and coke car over coke bin, skip hoist, furnace, cast house and hoist house.

Hoisting Appliances: The old time method of charging by hand having been almost entirely superseded by automatic mechanical charging, there are now in use two types of these devices, namely, the skip hoist and the bucket hoist. In both cases there is an incline, a fabricated steel structure, extending from the top of the furnace to or below the bottom of the stock house; and over the tracks of this incline the materials charged into the furnace must pass. In the skip hoist, the conveying vessel is a small open-ended steel car, called a skip, that automatically dumps the materials upon the little bell-and-hopper. Skip hoists are generally provided with double tracks, so that while a loaded skip is passing up the incline an empty one is descending. In the bucket hoist the solid materials are raised in a bucket, suspended from a truck or carriage, that drops the charge directly into the space above the large bell. When in position for dropping the charge, the bucket, being itself provided with a small bell at the bottom, takes the place of the little bell and hopper. During the time the bucket is filling at the stock house, the opening left in the top is closed with a special gas seal.

Top Appliances for Distributing the Stock: It is apparent that, in a mechanically filled furnace, when the raw materials are dropped into the receiving bell, the larger lumps of ore and stone will have a tendency to roll and thus collect either around the edges or to one side or the other. The same things will also happen upon dropping the charge into the furnace. This tendency results in more or less open and continuous channels being formed through the materials and extending from the top towards the bottom of the stack. These channels offer less resistance to the passage of the blast than the remainder of the materials, with the result that a disproportionate quantity of gas passes through them. This condition, called channelling, results in higher temperatures throughout these passages, with the consequent cutting away of the walls where these channels come in contact with them. To overcome this defect, various plans and devices have been employed to introduce the materials into the furnace in such a way that this segregation of coarse and fine material will not occur. With the bucket hoist, the plan so far found most effective consists in rotating the bucket during the time it is filling in the stock house. With the skip hoist, the scheme that promises to become the most widely used involves the use of what is known as the revolving top, in which the small bell and hopper may be rotated through predetermined arcs while the various skip-loads of a charge are being dropped upon the big bell. In this way the segregations due to dumping can be distributed about the periphery of the big bell, thus avoiding the separation and collection of coarse and fine materials in different segments of the furnace. To facilitate the dumping of the skip, a stationary receiving hopper is placed above the rotating hopper, with its funnel about the central axis so that the material of each skip is delivered over and upon the apex of the small bell.

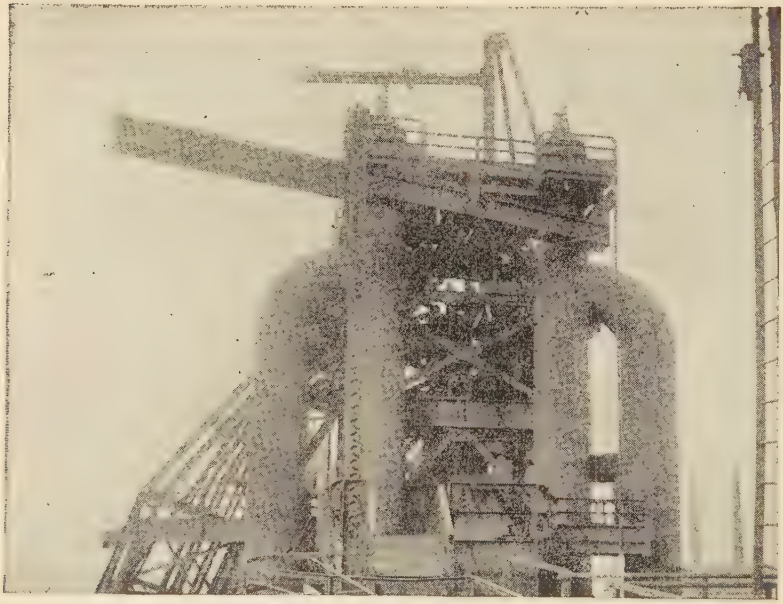


FIG. 47. Close up View of Furnace Top with Drop Bucket Hoist. Showing two, each, of the four vertical offtakes and downtake pipes. In this type of top the explosion doors are placed at the tops of the offtakes, which are also made to serve as bleeders.

Top Openings: The smallest opening in the top of a furnace is the **try-hole.** In operating a furnace it is necessary to be able to determine the position of the stock line. This is done by means of the **stock indicator,** which is a rod of steel passing through and fitting the try-hole loosely so that one end rests upon the stock, while the other is attached to a small steel cable that leads to the stock house or the cast house below. Some stock indicators are automatic and self-recording. For the escape of the gases, from two to four large openings, called **offtakes,** are provided. They pierce the furnace top just beneath the large bell. From these openings, about four feet in diameter, lead fire-brick lined pipes which converge into one large pipe called the **downcomer** or **downtake.** Into openings, either in the offtake pipes or in special openings in the top, are inserted the **explosion doors.** These doors, located usually in the ends of upright pipes arranged so as to prevent ejection of material from the furnace, are really valves which are adjusted, either by weights or by a mechanical means, to open at a certain pressure. They are designed to relieve pressure and so prevent possible injury to the top by slips in the furnace. **The bleeder** is a tall vertical pipe, usually inserted on the higher surface of the offtake pipe leading to the downcomer, to allow surplus gas to escape. It is closed with a valve on the top, which opens automatically, and may also be opened from the ground. Bleeders are usually lined with one course of fire brick.

FIG. 48. Another View of the Furnace Top Shown in Fig. 47.

General Consideration for Top Construction: As previously pointed out, there are many types of top, and the description above is intended to give a general idea of the essential parts and their uses only. The chief endeavor in top construction is to perfect the distribution of the stock entering the furnace stack, and either eliminate or compensate for as many irregularities as possible. However, in attaining this end, simplicity must be considered, as any great amount of mechanism on the top of a furnace is objectionable. It is important to prevent large material from being thrown out of the furnace in case of slips, and as little dust as possible should be carried out by the gases. Hence, in the most recent construction, the offtakes enter vertical **uptakes,** closed at the top by explosion doors, and are taken off the furnace as high above the stock line as possible, preferably at four points equally spaced on the circumference. The downcomer connections are taken off part way upon these uptakes. In locating the uptakes in furnaces of most recent construction, care is taken to see that they do not enter the furnace directly over the tapping hole, cinder notch, or the entrance of the blast main to the bustle pipe, because, these being the most active points in the furnace, this arrangement will tend to give a more even distribution of the gases through the stock.

Runners: Though not given much prominence in blast furnace discussions, the runners, through which the slag and metal are carried away from the furnace, constitute an essential part of the furnace proper. These are metal castings in the form of deep troughs which are made in sections laid end to end and buried so that their top edges are flush with the floor of the cast house. The trough leading from the cinder notch will, of course, be elevated. It forms an uninterrupted passage for the slag from the cinder notch to the slag ladle or granulating pit. The metal runner is more complicated. Beginning as a very deep trough at the tapping hole, it is interrupted at the end of about 10 feet by the **skimmer,** a device for separating the metal from the slag that comes near the end of a cast. There are two branches here, one for carrying away the slag and another for draining the metal from this part of the skimmer trough after the cast. From the skimmer the main trough is drained by branches leading to casting beds on the floor of the cast house, or what is more common now, to hot metal ladles on a track far enough below the floor of the cast house to permit the metal to flow into them from above. Before casting, these troughs are given a heavy coating of a loam or clay wash, which acts as an insulator, protects the trough from the hot metal and facilitates the subsequent cleaning up. Without this wash the hot metal would either chill in the trough or melt it away.

SECTION V.

BLAST FURNACE ACCESSORIES.

The Stoves, of which there are nearly always four to a furnace, are first in importance under the heading of accessories, being an absolute necessity in modern blast furnace operations. This importance is due to their function of heating the blast. The first stoves used were constructed of iron pipes enclosed in a brick structure through which the blast passed to the furnace, the gases from the furnace being burned as they circulated outside and around these pipes, the recuperative principle. Then it was found that the regenerative principle is much more efficient, so that now stoves are built entirely of brick. Essentially they are brick walled cylinders, enclosing a combustion chamber and a system of regenerative flues. Externally, the brick wall of a stove is reinforced and supported by a steel shell of riveted plates. The top of the stove is dome-shaped. Generally, the stoves are as high and almost as wide as the furnace itself. They vary in size with the size of the furnace. For the largest furnaces they are approximately 100 feet in height and 22 feet in diameter. Internally, the combustion chamber will extend from the bottom to the top of the stove, and may be located at the center, in which case they are called **center combustion stoves,** or at the circumference, as in **side combustion stoves.** The regenerative flues are filled with brick checker work, the checkers being so laid as to form a system of vertical flues, from five to nine inches square, which extend from the rider walls on the bottom to the top of the stove. The arrangement of the flues also furnishes a means of classifying stoves. Stoves in which the gases from the combustion chamber pass through only one regenerative flue, are called **two-pass** stoves, while in **three-pass** and **four-pass-stoves** they pass through two and three regenerative flues, respectively. Two-pass and three-pass types are the most common. Since the combustible gases are burned at the bottom always of all stoves, it follows that in two-pass stoves the products of combustion, passing through the checkers, must leave the stove at the

bottom, hence the opening to the stack on two-pass stoves is at the bottom. At some plants, stoves of this type are provided with individual stacks which rise along the side of the stove, but in other plants underground flues from a number, usually a set of four, of such stoves empty into a single stack, centrally located. In the three-pass type the hot gases are returned to the top of the stove, there to escape through an opening in the dome into a stack which tops the stove.

Stove Burners and Valves: Since the checkers in stoves are alternately heated by the products of combustion of a gaseous fuel in their passage to the open and cooled by the passage of the air or blast in an opposite direction and under pressure, a system of burners and gas tight valves are required. The burners are usually very simple in construction, consisting of a movable goose-neck mounted on a rack attached to the terminal of a vertical section of an underground gas flue in such a manner that the horizontal portion extends into a gas port in the side of the stove. A plate, or valve cover, is attached to the base of the goose-neck or the rack, so that racking the goose-neck back and forward automatically closes and opens the connection to the gas main. There are a number of more complicated and patented burners in use, which aim to increase the efficiency of the stove[1]. The valves present such a variety of forms that a detailed description of all cannot be attempted. The essential ones are named from their location. The **gas valve** has already been described in connection with the burner. The **chimney valve** is located at the base of the stack, its office being to prevent the escape of air through that opening when the stove is on blast. In three-pass stoves this valve is controlled from the ground by means of chain, or cable, and pulleys. The **cold blast valve** is located in the air line, which branches from the cold main from the blowing engines at a point just ahead of its entrance into the stove. As it is never subject to high temperatures, an ordinary form of gate valve may be used. In the three-pass type of stove this valve will also be at the top. The **hot blast valve** controls the exit of the blast from the stove through which the air passes. The blast being highly heated at this point, the hot blast valve must be constructed to withstand high temperature. It is usually of the mush-room type, and water cooled.

Other Stove Openings: Besides the openings mentioned above, the stove will be provided with a **blow off valve** to relieve the pressure and provide partial escape of air on changing the stove from air to gas. This valve may also regulate the admission of air for combustion. Numerous **clean out holes,** through which the flue dust that collects in the stove while it is being heated may be removed, will be placed at points most desirable for the purpose.

[1]See Modern Methods of Burning Blast Furnace Gas by A. N. Diehl. Year Book of the American Iron and Steel Institute, 1915.

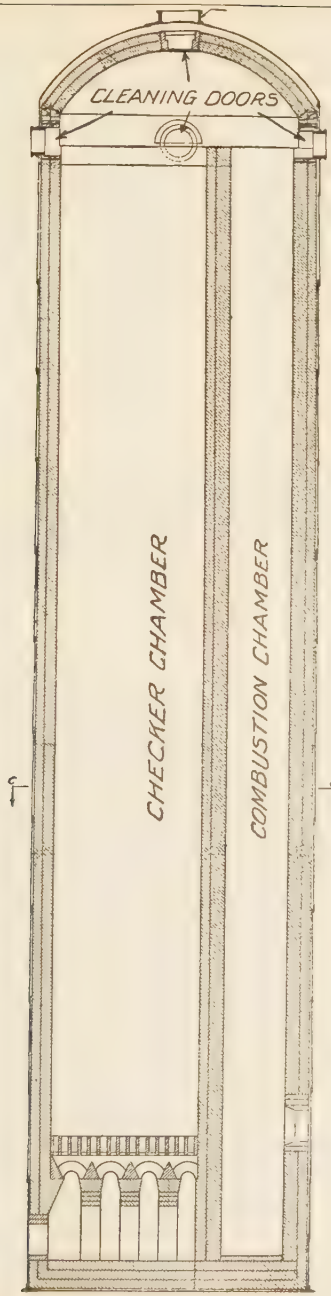


Fig. 49. Vertical Section of Standard Blast Furnace Stove. Two-pass Side Combustion Type.

Stove Linings: Stove linings is a term that corresponds to furnace lining, and includes all the brick work enclosed by the shell. As in the case of the furnace, an expansion space of about two inches is left between the circular brick wall and the shell. For these linings a strong yet porous firebrick is required, because such brick absorbs the most heat and also gives it up most readily. The brick need not be very refractory, for the temperature in the stove is relatively low except in the combustion chamber, where a brick possessing fairly high refractory properties is required. The temperature of the hot blast is maintained at about 538° C. (1000° F.) which marks the lowest temperature to which the hottest part of the stove

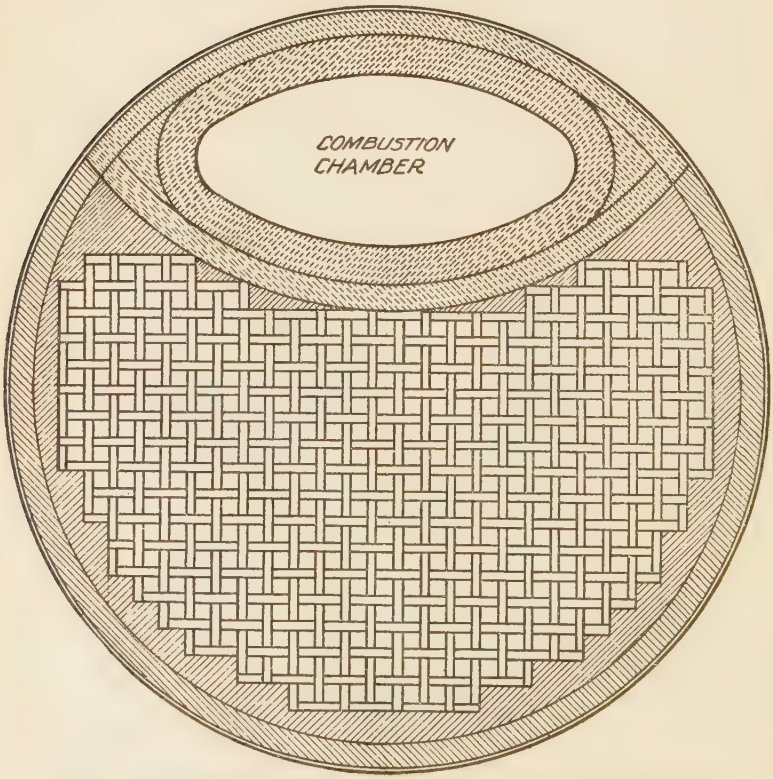


Fig. 50. Cross Section of Blast Furnace Stove. Section C C of Fig. 49.

can drop. With modern stoves, from 25 to 30 per cent. of the gas produced by the blast furnace is required to maintain the blast at the correct temperature. Of the remainder about one fifth, (12 to 20% of the whole) is used by the blowing engines, so that a little more than half of the total gas produced by the furnace is available as surplus for the generation of electrical power.

Dust Catcher and Gas Mains: From the down-comer the gas from the furnace passes directly into the dust catcher. Its object, as implied by its name, is to clean the gas as much as possible of the flue dust blown over from the furnace, with which dust the gas is heavily laden. If this dust is not removed, in part at least, it cakes upon the walls of the combustion chamber and small flues of the stoves and, dropping down, necessitates frequent cleaning. Besides, it acts as an insulator on the brick, preventing the full absorption of heat. Similar conditions also prevail when the dirty gas is burned under boilers. The dust catcher may be looked upon as a great enlargement of the flue, or down-comer. Its diameter is often 20 feet or more. It is brick lined, often has a dome shaped top, and a bottom in the shape of an inverted cone. The principles involved in its construction is that of greatly reduced velocity accompanied by sudden change in direction. By this means the dust in the gas may be reduced sufficiently to be used under boilers and in stoves with large flues very satisfactorily. From the dust catcher the gas passes through a gas main that divides into two branches—one to supply the stoves and one to furnish gas to the boilers for generating steam, which disposal will now apply to the older and less progressive plants only. In up-to-date plants, the gas will be subject to additional and more efficient treatment, after which it may be used in the two ways mentioned or in internal explosion engines. This additional cleaning of the gas is a necessity where gas engines are used, and it is also claimed that gas for the stoves is cleaned at a profit, since it eliminates the necessity of frequent cleaning of the stoves and permits smaller checker flues, thus increasing the heating surface of the brick. The matter, while past the experimental stage, is not yet fully developed at all plants. As representing a highly developed method of gas cleaning, the Duquesne works will furnish a good example.

Arrangement of Furnaces and Cleaning Plant at Duquesne: At this plant there are six furnaces situated in a row, for the full length of which extends a large gas main, called the rough gas main. The gas from all these furnaces may enter this main after passing the dust catchers. From this main, gas may be led to any part of the plant to be used in the raw state, though it is primarily intended to supply the cleaning plant. The flow of the gas through the main is controlled by water valves. A water valve is a vertical cylinder with a cone-shaped bottom; in its center is a vertical diaphragm reaching down over half way to the base of the valve. Water can be admitted into the valve to a level somewhat higher than the lower edge of this diaphragm. With the water level below the diaphragm an outlet is provided so that a current of gas may be allowed to flow through; when water rises high enough above the base of the diaphragm to resist

the pressure of the gas and prevent its passage under the diaphragm, the valve is sealed. By means of these, any furnace can be shut off from the system. The gas cleaning plant consists of two divisions called the Primary

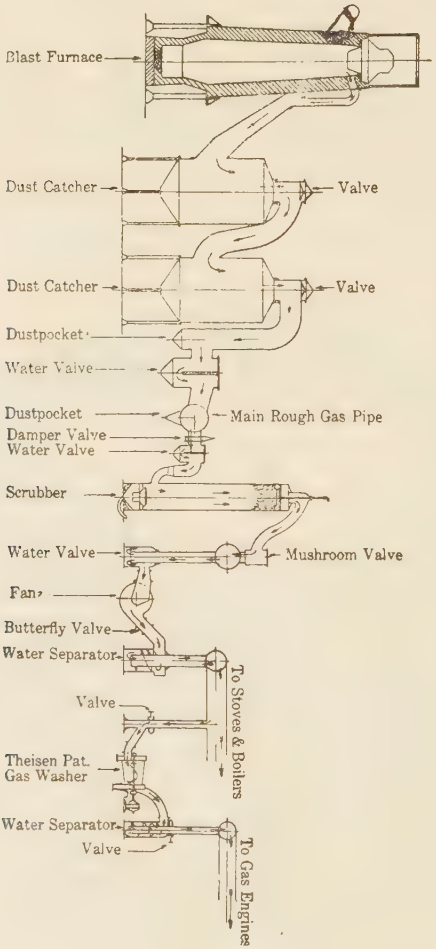


Fig. 51. Diagram showing Route of Gas from Furnace through Gas Cleaning Plant to Boilers, Stoves and Gas Engines. Carnegie Steel Company, Duquesne Steel Works.

and Secondary. The primary division receives and washes all the gas that is brought from the furnace by the rough gas mains and returns the washed

gas to the stoves or boiler houses when desired. The secondary division receives only such gas as is intended for use in the gas engines.

Primary Division: The primary cleaning of the gas is accomplished by vertical water scrubbers and fans. It reduces the dust content of the gas to .06 grain per cubic foot of gas under standard conditions. The vertical water scrubbers are the most important part of the equipment in respect to the amount of dust removed from the gas. There are nine of them, and the gas connections for them are led to their bases from the gas main through water-and damper-valves. These scrubbers are vertical steel cylinders, unlined, 77 feet 6 inches high and 12 feet in diameter, and are built of $\frac{5}{16}$ inch steel plates. Gas is admitted at the base. Water is admitted so as to fall against the gas, and, as the currents flow in opposite directions, there is intimate mixture between them. The water is applied to the gas in the form of a spray and when falling in the interior of the scrubbers is like rain in that it is in small drops and thus presents the greatest possible surface to the gas.

Methods of Scrubbing the Gas: Two methods of producing and supplying the water spray have been used at this plant. The older method employed a horizontal spray pipe located in the top of the tower and rotated by a small electric motor. Water was supplied to it from a pipe inserted at the top. The falling water was prevented from striking the shell by a vane in the bottom of the spray pipe. Just below the spray pipe were 12 screens set together so as to break up the water stream as it fell, but from that location the spray fell uninterrupted to the base, where it was drained out through a gas seal. In the improved form, two series of seven pipes each are inserted one above the other. The water is forced up through screens placed at six-foot intervals and must then fall back through them. Motor-driven cut-off valves shut off the water from each pipe in turn, making an area of low resistance over the pipe from which water has been cut off. The gas rushes to this region; then water is turned on again and the gas is deflected. A spiral motion results, giving a larger exposure of gas area to cleaning water than would ordinarily result. The scrubbers use about 6,000,000 gallons of water per 24 hours. The temperatures of the gas entering the scrubbers range from 300° to 600° F., and the pressure varies from 8 to 16 inches of water. The water enters the scrubbers at river temperature and at an average of 57.4° F. with a maximum of 84° F. and a minimum of 33° F. The dust caught in the settling basin, which is built in duplicate and extends from one end of the plant to the other, averages half to three-quarters of a standard 50-ton hopper car a day. The gas passes at a velocity of four feet per second up through the steel shell into a pipe connecting with a 10-foot 6-inch main. The gas leaves at a temperature varying from 96° F. to 37° F., or at an average of 68°F. The dust in the gas is reduced from 3.5 grains per cubic foot to .22 grain at standard conditions; the moisture in the gas entering the scrubbers is 34 grains per cubic foot and on leaving is 8.5 grains. About 25 cubic feet of gas is cleaned per gallon of water used.

The Fans: From the scrubbers, a large gas main, 10 feet 6 inches in diameter and about 40 feet above the ground, conveys the gas to a number of fans that complete the primary cleaning of the gas. The connections to these fans are provided with water valves. The fans are located in a gas cleaning building, or fan house, and are four in number. Each fan has a rated capacity of 84,000 cubic feet of gas per minute at 100°F. The fans raise the pressure of the gas to about six inches of water and thus give it sufficient head to pass through the entire system of stoves, boilers and engines; the furnace pressure alone is not sufficient to supply this head. The gas leaves the fans at temperatures varying from 93° F. to 35°F., or an average of 69° F. By introducing water at several points into the shell of each fan, the fans are made to serve as cleaners, and the dust content of the gas is reduced from .22 grain per cubic feet to .06 grain per cubic feet.

Water Separator: From the fans, the gas passes through water separators. These are made of two concentric steel cylinders which stand in a vertical position. The outer cylinder is much larger in diameter than the inner one and somewhat longer, so that the gas, entering at the top of the outer cylinder and on a tangent, is given a downward spiral motion and escapes at the bottom rising through the inner pipe. In this way, the greater portion of the water, owing to its greater inertia, is deposited by the gas current. From the water separator the gas enters the clean gas main and is distributed to the stoves and boilers and also to the secondary division.

The Secondary Division: This division furnishes gas for internal combustion engines, which require gas almost as free from dust as the air itself. It consists of four Theisen cleaners. This cleaner is a combination fan and cleaner. Externally it has a form approximately like that of a large steel cylinder and is mounted horizontally. This outer cylinder is stationary and encloses a similarly shaped but smaller revolving cylinder on the shell of which is riveted twenty-four steel vanes. These vanes project 12 inches from the shell of the inner cylinder and extend longitudinally in a slight spiral to the circumference. At the receiving end the vanes project beyond the end of the cylinder to form a drawing fan for receiving the gas, while at the delivery end they terminate in blades, attached to the same cylinder, that act as a booster fan for propelling the gas through the succeeding apparatus. Water is admitted at low pressure through six pipes half way up and on the side of the outer shell. This water is dashed to a spray by the revolving vanes, and, being propelled in a direction opposite to that of the gas, is thoroughly mixed with it, thus wetting the last small particles of dust, which must, therefore, separate with the water. This water is let out of the apparatus through a water seal at the bottom. The gas flows through the shell and out into a water separator, thence to the gas main leading to the gas engines. The Theisen cleaners have a rated capacity of 14,000 cubic feet of gas per minute at standard conditions. The gas leaves the Theisen at an average temperature of 64.2° F., or a maximum

of 91° F. and a minimum of 35° F. The water enters at an average of 57.5° F. The dust in a cubic foot of gas is reduced from .06 grain to .009 grain. 45.44 cubic feet of gas is cleaned per gallon of water consumed.

SECTION VI.

EQUIPMENT FOR HANDLING RAW AND FINISHED MATERIALS.

The Boiler House, Power Plant, Pumping Station, Blowing Engines, etc. while constituting a very vital part of the blast furnace equipment present features of more interest to engineers than to metallurgists and are therefore, best omitted from this discussion.[1]

Dry Blast: About 60 per cent. by weight of all the materials entering the blast furnace is air. As air always contains moisture and since the decomposition of water is an endothermic reaction, the heat absorbed by the amount of water thus entering the furnace may be very great. It has been estimated that during the month of July, for instance, the average quantity of water, per hour, entering a furnace using 40,000 cubic feet of air per minute is approximately 224 gallons. That this quantity of water may seriously affect the operation of the furnace is now well recognized, and installations for drying the air have been made at a few plants. Without discussing in detail the apparatus used, the principle employed is that of refrigeration. By cooling the air to a low temperature by drawing it over a system of pipes cooled with brine, (a solution of common salt, NaCl, or calcium chloride, $CaCl_2$, which has a less corrosive action on the pipes), which in turn is cooled with liquified ammonia, the moisture is condensed and frozen on the pipes, leaving the air practically dry.

Cold and Hot Blast Mains: It is still the most common practice to use undried air, which, compressed by the blowing engines, is forced normally under the high pressure of about 15 pounds per square inch through the cold blast main into the stoves, from which it issues highly heated; and passing successively through the hot blast main, the bustle pipe and the tuyeres, begins its work in the furnace. In this connection one or two apparently minor details of construction referring to temperature regulation and pressure control should be noted. Leading around the stoves from the cold blast main into the hot blast main is a small pipe called the **by-pass.** It provides a means of controlling the temperature of the hot blast. The **snort valve,** also located in the cold blast main, is used to reduce the pressure of the blast at the end of a cast while the tap-hole is being stopped, or to release the pressure in case of a hanging furnace. For regulating the temperature of the blast, a recording pyrometer couple is inserted into the hot blast main at a point near its entrance to the bustle pipe.

[1]For details on construction of the blast furnace and equipment, see Blast-Furnace Construction in America by J. E. Johnson, Jr., published by McGraw-Hill Book Company, New York.

Appliances for Handling Ores, Coke and Stone: As was pointed out in Chapter III, all ore is shipped over the Lakes from May until December. Consequently the ore required to operate the furnaces during the months intervening between shipping seasons must be stored until used, either at the docks or at the works. This storing of ore requires a stock

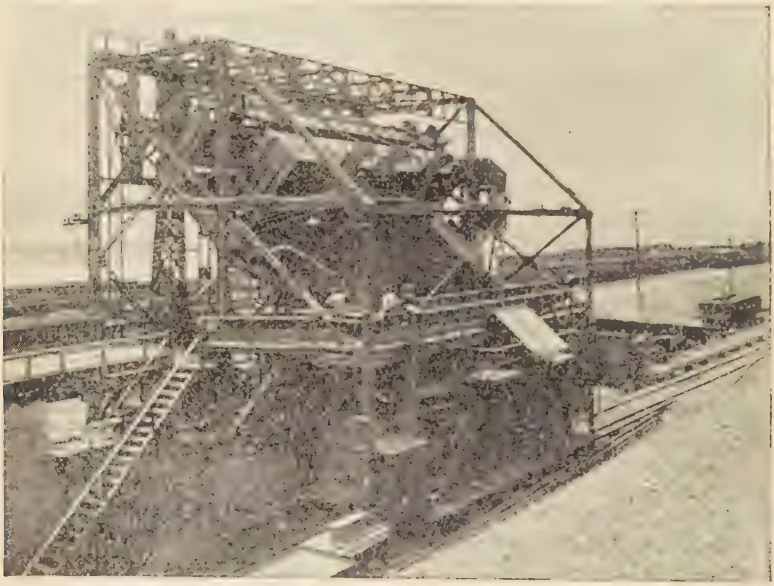


FIG. 52. View of Car Dumper in Operation. Showing ore being dumped from railroad car to ore transfer car.

yard with suitable provision for an ore pile, rapid means of unloading cars, and convenient and economical methods and appliances for handling large quantities of ores. For unloading the cars, **car dumpers** have been installed, while for piling and delivering the ore to the bins over the stock house, **ore bridges** are employed. The ore, arriving at the works in train load lots, is switched to a siding ahead of the car dumper, and the cars are unloaded one by one in rapid succession. A car, being pulled up an incline to the platform of the dumper, is bodily lifted and turned over so as to empty its contents into large larry cars, or into bins, if small larry cars are used. The dumper then resumes its former position, and the car is pushed off the platform by the next car of ore to an incline, down which the empty car moves to a car siding. Larry cars, designed for the purpose, carry the ore to the ore pile, where the ore bridge picks up the ore and dumps it in its proper place in the pile. The details of this operation will vary much, but the general scheme is essentially as stated. Aside from the mere storing of the ore other aims, while more or less incidental, must be

kept in mind. In order to obtain uniform conditions necessary to keep the furnace operation under good control, it is desirable to mix the ore of each kind or grade as much as possible; again, the uniformity of the ore may be affected by dumping on large, sharply peaked piles, because dumping in this manner causes a separation of the coarse and the fine material, which always differ widely in chemical composition. For similar reasons, the use of ore direct from hopper cars unloaded from the trestle into the bins is undesirable. The ore is the only material stored, both the limestone and the coke being brought in as required. All up-to-date plants are provided with an ore trestle running out over the bins above the stock house. The bins are used for storing smaller amounts of ore, fuel and flux, which are then conveniently available for immediate use. The bins are large hoppers, the bottom openings of which are closed in such a way as to permit the withdrawal of fixed quantities of materials as desired. The bins for the three materials are alike except that those used for coke are provided with screens for removal of the "fines." In the most modern plants the open tops of the bins are covered with a heavy grid-iron grating, which serves the two-fold purpose of preventing accidents, resulting from workmen falling into the bins, and the stoppage of the chutes below, due to oversize pieces of material that might otherwise be dropped in.

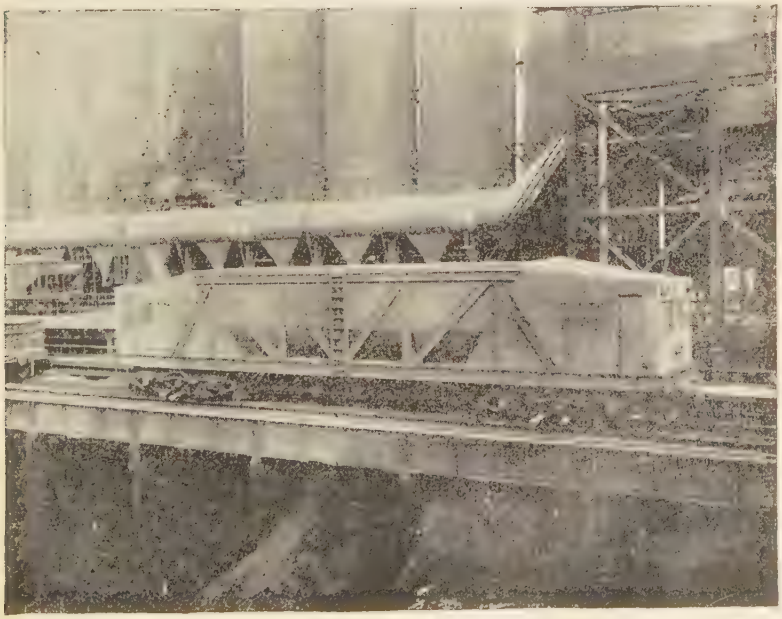


FIG. 53. View of Stock House, Looking from the Ore Pile. Showing transfer car dropping ore into ore yard. Blast furnace gas main and stoves for two furnaces in the background.

Stock House Equipment: Under the trestle and bins is a large space known as the stock house. Here are found the mechanical devices which have superseded the old and original method of charging by hand. The equipment will be different for each type of hoist. If the skip hoist is in use the arrangement in general will be as follows:—The skip tracks will extend down beneath the floor of the house far enough to permit the lowering of the skip beneath chutes, which lead from the floor so as to deliver the materials into the mouth of the skip. These materials will be delivered to the chute by means of a small trolley car, running on tracks that extend under the bottom openings of the bins. This car—a small hopper car—is provided with a scale to weigh the ore and stone as it falls into the hopper of the car. In this way any mixture of ores or stone desired may be accurately made up by weight for charging. In the bucket hoist the same scheme as that just described is used for collecting the ores and limestone, but the bucket itself is placed, on descending, upon a revolving device, which keeps the bucket revolving during the time it is receiving the charge. Only the ore and stone are weighed, the coke being charged by volume.

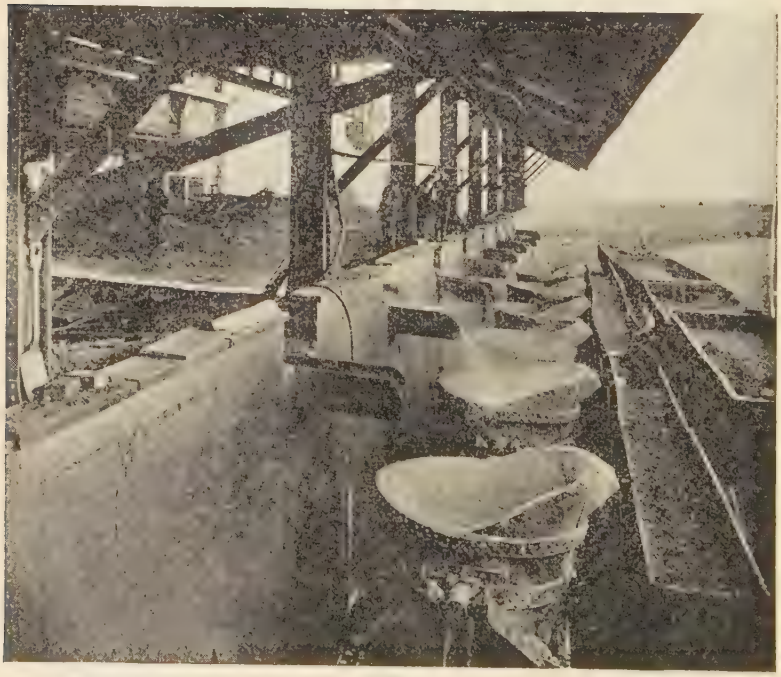


FIG. 54. Cast House. Showing iron flowing into ladle just after the furnace has been tapped.

Disposal Equipment for the Iron: The old method of casting the metal in beds of sand has, for many reasons, been replaced by casting machines. Of the two types of these machines, the endless chain carrying a series of parallel moulds or troughs with over-lapping edges is the one most commonly used. In the operation of this machine, the molten metal from the furnace is allowed to flow into ladles, which are pulled at once into the casting house. Here, the metal is poured slowly into a trough from which it flows onto two lines of moving moulds, which have been previously prepared, to prevent sticking of the iron, by being either "limed" or "smoked." The chains may carry the iron directly through a trough of water, or dump the half cooled pigs upon a second conveyor to be so cooled. A number of modifications of this machine are in use. In the case of furnaces operating in connection with steel works, the casting machine is used only as occasion demands, the iron regularly being transferred directly to a mixer while it is still in the molten state.

Equipment for Slag Disposal: The greater portion of the slag produced cannot be used except as waste, so most of it will be transported while molten to a convenient spot and dumped. After weathering several months, this slag may be crushed for use as railroad ballast, road building material, or concrete aggregate. As an aggregate for concrete work, crushed slag is unsurpassed; it has the strength required, and possesses a texture that enables the cement to form a better bond with it than with either broken stone or gravel. When the slag is to be used for certain purposes, as for making Portland cement, it is best granulated. This condition is produced as the slag flows from the furnace by allowing it to fall into a large concrete lined pit, partly filled with water and known as the granulating pit. By forcing a small stream of water against and from behind the stream of molten slag as it drops into the pit, the stream of slag is broken up and the fineness of the slag is increased. Merely allowing the slag to fall into the water is a much less effective method.

SECTION VII.

OPERATING THE FURNACE.

Blowing In: Upon being completed and provided with as much of the equipment described above as is necessary or desired, the active career of the furnace is begun. In blast furnace parlance, the process of starting a furnace is called blowing in. It is carried out in three steps; these steps are drying, filling and lighting.

Drying: Newly constructed furnaces and stoves, or new linings, must be carefully and thoroughly dried before they are put into operation. In the case of the blast furnace, any one of three methods may be employed. In one, the drying is accomplished by means of a gas fire in the hearth, natural gas, coke oven gas, or blast furnace gas being used for the purpose. With this method precautions must be taken to keep the gas burning, for if the flame should be extinguished, the furnace is liable to become

filled with an explosive mixture of the gas and air. To guard against such eventualities, some furnacemen employ pilot fires in the hearth while others use brick checker work over the burners, and in addition a man will be delegated to keep constant watch of the fires. A second method is to build three or four Dutch Ovens at different points outside of the hearth, fire these ovens with gas, coke, or a mixture of coal and coke, and allow the products of combustion to be drawn through the cooler openings into the bottom of the furnace. This method, while it is safer than the gas fires, is more troublesome, requires more labor, and is probably more expensive. The third method makes use of the hot blast for drying. In carrying out this method the stoves are heated as when the furnace is operating, and air from the blowing engines is passed through the stoves, then to the bottom of the furnace through the regular connections and a number of special pipes extending from the tuyeres inside the furnace to the bottom. While this method eliminates all possibility of explosions, it can be used only in large plants where excess gas is available for heating the stoves, and is not practicable when the drying must be extended over indefinitely long periods of time. During the drying out, the openings at the bottom of the furnace are kept covered to prevent the drawing in of an excessive amount of air, while the bleeders at the top are kept open. When using gas for drying, some operators will also lower the bells. In all cases the heat must be applied very gradually. About ten days are required to complete the drying, but when it is feasible to do so, this time may be prolonged to two weeks or more. Following the drying period, the drying out fires must be kept up until such time as the furnace may be put on blast.

Filling: After the furnace is sufficiently dried, it is allowed to cool slightly, and then the important process of filling is begun. While different individuals will pursue slightly different methods, the general scheme will be rather uniformly carried out. Briefly stated, it consists of first placing wood and coke, or coke alone, on the bottom to a height somewhat below the level of the tuyeres, about which any easily ignited material, preferably charcoal, is piled; then following this material with a large quantity of coke, mixed with enough limestone to flux its ash, and gradually introducing ore with the proper amount of flux. Good practice requires that this initial volume of coke should be about half the cubical contents of the furnace. Sometimes, to get an easily fusible slag and a good volume of it, blast furnace slag may be introduced ahead of the ore. These are called the blowing-in burdens, and additions are made till the furnace has been filled to the stock line, when it is ready for **lighting.**

Lighting: Starting the burning of the materials in the bottom of the furnace may be done in several ways. If the space in front of the tuyeres has been filled with light kindling wood, as is customary, oil is poured or sprayed in at the tuyeres until the wood is thoroughly soaked with it. Then with all the gas burners and valves in the gas mains and the bells closed,

the bleeder and explosion doors are opened, a light blast is turned on and the wood ignited by inserting hot bars through the tuyeres. Often, instead of the hot bars, a wood fire is built in the stove nearest the furnace, and the oil is ignited by blowing sparks over with the blast. With a light blast on, the wood soon burns away, and the stock begins to settle, after which the blast pressure is gradually increased. Some furnacemen start off, after the fires are well caught, with a fairly high blast pressure for a few minutes, in order to drive the flames well in toward the center of the furnace and consume the wood quickly, as it is thought that a better initial settling of the stock is thus obtained. As soon as the stock gives signs of settling, the blast pressure is reduced to that normally used for the remainder of the blowing-in period, which is at first about ¼ that used when the furnace is in full blast. Up to this point a great deal of gas and smoke escape from the furnace openings, and great care must be exercised, for the gases contain a high percentage of carbon monoxide, and are very poisonous. Great care is also required to prevent explosions, because mixtures of furnace gas and air in a wide range of proportions are explosive. Since the interstices of the stock in the furnace and all the gas mains are filled with air to start with, an explosive mixture may be formed any time soon after the lighting, and if this mixture should be ignited it might cause serious damage. The difficulty is generally overcome by providing outlets for the gas at the ends of the gas mains. These outlets are kept open until all the air has been expelled, which condition is indicated by the color and odor of the escaping gas. Both men and fires are kept away from these openings until it is time to use the gas and the outlets are closed.

Heating the Bottom: Another feature connected with the lighting of the furnace is **heating up the bottom,** which is warmed by the drying-out fires to only a slight degree as compared with the temperature required to keep the slag and iron that form in a molten state. In order to have the bottom at the proper temperature when slag begins to form, two methods are employed, both of which involve leaving an opening at the tapping hole so as to draw the flame downward from the tuyeres upon the bottom. In the first method a round tapered wood plug, three or four inches in diameter at the smaller end, is placed in the tap-hole and the space about it is packed full and tight with clay. With the rise in temperature due to the burning of the wood and coke in the bottom, the clay sets, and this plug is then removed, which permits the flame from within to shoot forth, thus heating up the runner outside as well as the bottom inside of the furnace. When slag begins to flow from the tap-hole, the opening is closed until time for tapping the first iron has arrived. In the second method, an iron pipe, about four inches in diameter, is placed in the furnace, before it is filled, so that one end protrudes from the tap-hole outside of the hearth, while the other extends to the center of the furnace. The space about the pipe where it passes through the wall of the hearth is

tamped with clay or ball stuff, which is also built up about the part of the pipe within the furnace for a foot or so from the hearth wall. When the furnace is lighted, the gas flame is drawn to the center of the bottom to pour forth from the exterior end of the pipe. This pipe need not be moved until a fairly large flow of slag is attained, when it is drawn from the tap-hole, which is immediately closed, as in the case of the wooden plug.

The Heating of the Stoves is another factor connected with the lighting of the furnace. The temperature of the hot blast when the furnace is in full operation is 500 to 550° C. (930 to 1020° F.), and it is a great help if the stoves can be heated nearly to this point for the lighting of the furnace, especially as the furnace and filling are cold to the bottom. But this stove temperature can be obtained by the use of gas only, so that in the case of isolated furnaces where gas is not available before starting up the furnace, the stoves must be heated as hot as possible for the lighting by means of wood and coal fires.

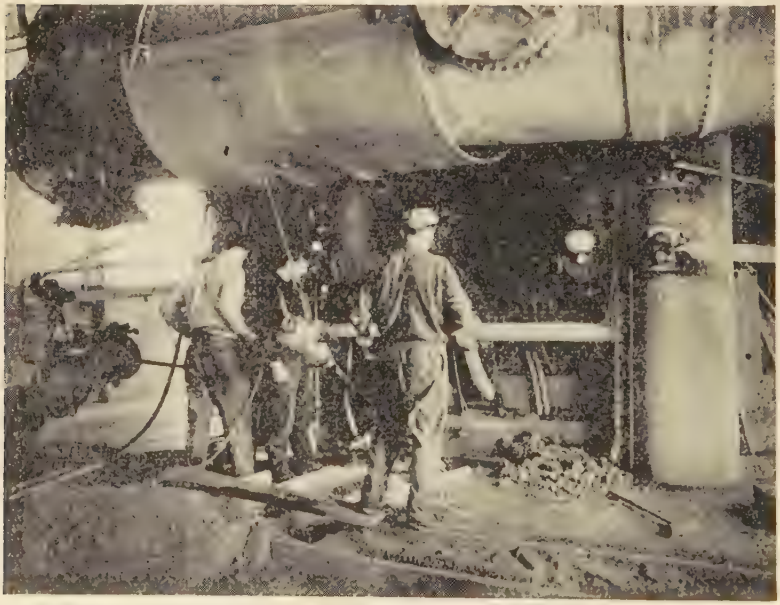


Fig. 55. Boring out the Tap Hole Preparatory to Tapping the Furnace.

Tapping: At the end of ten or fifteen hours after the blast is on full, there will be a sufficient accumulation of slag to tap. This is done by removing the bott from the monkey, and pricking through the solid slag closing the opening, if the cinder does not flow immediately. The bleeder is

closed after the first cinder is tapped, as the gas can now be used in the stoves, and boilers or gas engines. It requires from 30 to 40 hours before much iron accumulates. When the iron is ready to tap, a hole is bored by means of a long auger or drill, electrically or otherwise operated, almost through the clay plug of the tapping hole. During the boring, the dust is blown out of the hole by a jet of compressed air. The splasher having been put in place, the opening is then completed by driving a long pointed bar into the furnace or by burning out the iron plug with oxygen. As the latter

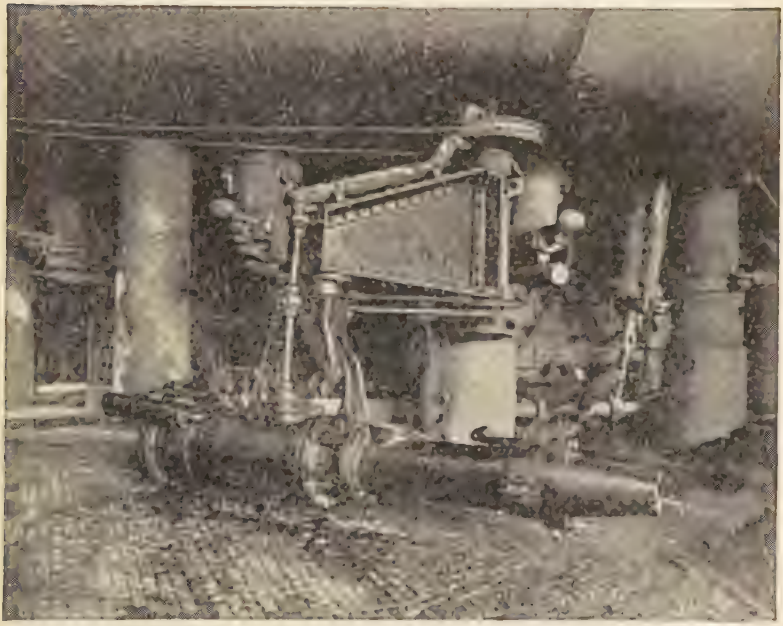


FIG. 56. View of Mechanical Clay Gun, charged and ready to be inserted into the tap hole.

method is quicker and saves much labor, it is the one generally used. If a bar is used, the iron will not flow out until the bar is withdrawn, when it will begin to flow slowly. As the flow of iron progresses, the opening is enlarged and the metal flows out rapidly. The iron will thus flow out through the runners under the skimmer to the ladles provided to receive it. During the flow of the metal, samples of the iron for chemical analysis and fracture tests are taken by collecting small spoonfuls from the main runner. The slag, which follows the iron near the end of the cast, is stopped by the skimmer, where it may be run off through a more elevated runner to the slag ladle or granulating pit. When the iron has almost ceased to flow

from the tapping hole, and gases are pouring forth, the blower signals the engineer to reduce the blast and opens the snort valve on the cold gas main to relieve the pressure. Then, the iron and slag having been drained from the skimmer, the **clay gun,** hung on a crane, is swung into the opening, either by hand or mechanically. This gun is provided with a steam cylinder which operates a rammer that forces a quantity of clay mixed with a little coke dust into the tap hole. The clay forms a plug that closes the opening. This plug of clay is then backed up with more of the mixture, which is fed into the gun, through an opening for the purpose, in the form of moist balls. As soon as the hole is stoppered, the snort valve is closed and the furnace goes on blast till next tapping time—four, five or six hours afterward.

FIG. 37. View of the Mechanical Clay Gun Stopping the Tap Hole at the End of a Cast

Care of Runners: After the tapping hole has been closed, from one to three minutes being required, the troughs are emptied, and preparations for the next cast are begun. The runners are cleaned carefully of both metal and slag, and their inside surfaces are carefully brushed with a thick clay or loam slurry which, when dry, protects the trough, and prevents the iron from sticking to the runner.

Sampling the Iron: Sampling pig iron is a very important part of every tapping. As the iron is graded by chemical analysis, care should

be taken to secure a sample for the chemical laboratory that will be representative of the whole cast. This sample, therefore, is generally made up of a number of equal portions taken from the main runner at the farther side of the skimmer and at periods corresponding to the middle of each ladle of metal in the cast. These samples may be in the form of shot made by pouring the molten metal slowly into water or upon a cold iron plate, or they may be small castings made by pouring the metal into a mould. In addition to these laboratory tests, samples called **sand tests** or **chill tests,** according to the manner of casting them, are also taken. In these tests the iron is allowed to cool in small moulds about two inches square in cross section and four inches long. The moulds may be either of sand as in "sand tests" or of metal, when they are called "chill tests." When cold, the small casting is broken with a hammer, and from the fracture thus exposed, if the test has been cooled properly, the blower is able, generally, to judge very closely as to the quality of the iron. Chill tests of all slags are also taken and carefully inspected.

Tapping Slag: In about two hours, the slag will have risen near the tuyeres, and another flush will be necessary. If the iron is tapped six times a day, only two flushings of slag are necessary between tappings, but if the tapping is on a five-hour schedule, three flushings will be required.

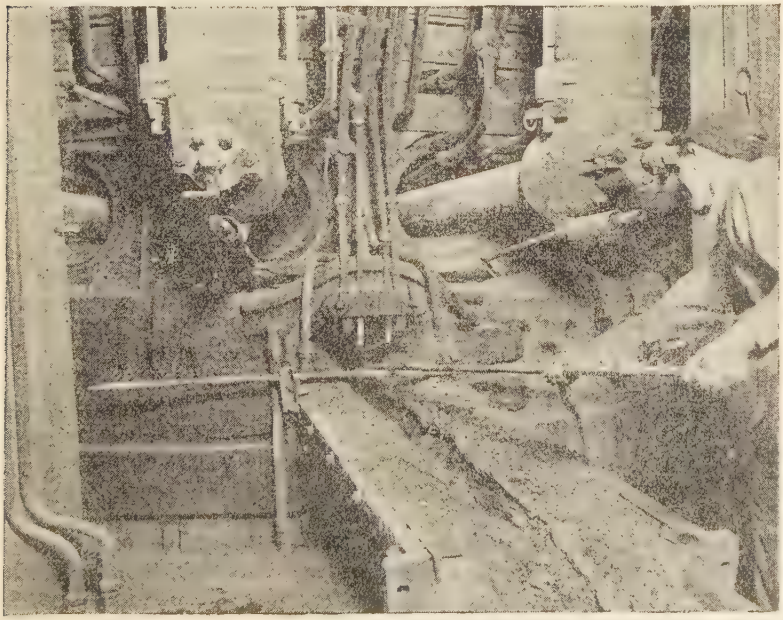


FIG. 58. Opening the Cinder Notch with the Hand Bott.

Changing Stoves: The temperature of a furnace at the hearth is a matter of great importance, as this is one of the two main factors which control the quality of the iron produced. One of the means of regulating this temperature is by changing the slag composition, as has been suggested. Another way by which quicker results may be obtained is by control of the hot blast temperature. This may be raised or lowered by use of the by-pass, and can be kept high by proper manipulation of the stoves. As a part of the routine of blast furnace work, the tending of stoves is of importance. They must be kept clean and be changed regularly and at not too long intervals. Usually but one stove at a time is employed for heating the blast, and the stoves are changed once each hour. Thus, each stove is heating for three hours. In changing stoves the hot stove must be put on the furnace before the cold one is taken off. To put a stove on hot blast, the gas burner is racked back from the gas port, and the **blow-off** and chimney valves are closed. Then in quick succession the cold blast valve and the hot blast valve are opened, when the blast is free to pass through the stove, which it does in the direction opposite to that by which the stove was heated. The cold stove is now taken off, the procedure being the reverse of the above. The cold air valve is closed, and then quickly, the hot blast valve. To relieve the pressure in the stove, the blow-off valve is slowly opened, which permits the chimney valve to be opened. The stove is then ready for the gas, which is admitted by racking the burner forward.

Charging the Furnace: The charging of the furnace is a part of the routine that must be done with great care and cannot be interrupted. The furnace tends to empty itself rapidly, and constant vigilance is necessary to keep the stack full. The proportions of the materials used are predetermined quantities. Therefore, all the materials are carefully weighed before charging into the furnace. The charging is usually done in **rounds.** The basis of charging is the weight of fuel in each round. The fuel remains a fixed quantity, and any variations in the charge are made with the ore and flux. Usually the coke in the round is measured by volume and not weighed, but, of course, the weight of the given volume in a round is known. The weight of this coke unit varies at different plants, because it is subject to no fixed rule, the opinions of furnacemen differ as what it should be, and it is affected by the size of the furnace and other conditions. The weights most often used are 10,000, 12,000, and 15,000 pounds. Under present conditions the weight of ore in the rounds will approximate twice and the limestone half the weight of the coke. The manner of charging the materials is also subject to much variation. Often it will be found that all the coke in a round will be charged, followed by the ore and limestone mixed together. To charge in this manner, each skip or bucket of coke is first dropped upon the small bell or placed over the gas seal which is lowered to allow the coke to fall upon the big bell. This operation is repeated until all the 10,000, 12,000 or 15,000 pounds of coke has been dropped upon the big bell,

which is then lowered, allowing the coke to drop into the furnace. The ore and stone are then charged in the same manner. To illustrate the variation to be expected in the manner of charging, the simple scheme outlined above may be compared with the following, which was once found in use at a certain plant.

1 skip of ore—mixture of ores A. and B. Weighed. **Small bell lowered.**

1 skip of stone and ore—mixture of stone and ore C. Weighed. **Small bell lowered.**

1 skip of coke—not weighed. **Small bell lowered.**

1 skip of coke—**small bell lowered.**

Big Bell Lowered.

1 skip of stone and ore—mixture of stone and ore C.—**small bell lowered.**

1 skip of ore—mixture of ores A., B. and C.—**small bell lowered.**

1 skip of coke—**small bell lowered.**

1 skip of coke—**small bell lowered.**

Big Bell Lowered.

Some Irregularities of Furnace Operation: The blast furnace, even in its highest development, is by no means the even-going, easily-regulated monster the casual observer may take it to be. Although furnace operations are under better control now than ever before, the furnaceman still refers to his furnace in the feminine gender, because, he knows she is a fickle maid capable of acting in most unexpected and astonishing ways. Therefore, a full discussion of this subject would lead to possibilities and probabilities almost without end. However, the subject lends itself to at least one positive statement. It is this: There are few situations in life where promptness and decision, forethought and good judgment, skill and experience are more needed than about a blast furnace in times of trouble. A few of these troubles are here enumerated.

Slips are due to a wedging of the stock in the upper part of the stack. They are thought to be caused by carbon deposition, which may, in some cases, be more in volume than that of the ore. This deposition fills up the interstices of the stock, so that the gas can penetrate it only with difficulty. When this condition occurs the stock beneath the wedged portion settles from that above, the blast pressure rises and the wedged stock finally falls. The sudden release of pressure on the gases produces a result like that of an explosion. Slips of great violence have been known to tear off the top and do very serious damage.

Scaffolding occurs near the top of the bosh. This condition is often due to irregularities in the working of the furnace, the following explanation

often being suggested: If the zone of fusion is suddenly lowered, the pasty mass at its top tends to adhere to the encircling wall, with the result that an incrustation is formed which projects toward the center of the furnace. This mass offers obstruction both to the gases and to the descent of the stock. If this condition is not soon remedied, the blast gases will channel, perhaps on one side, in which case serious damage to the lining would result. Dynamite is sometimes necessary to break a scaffold. This condition is often referred to as **hanging.**

Chimneying and Hot Spots: Chimneying is caused by the improper distribution of the charge with the coarser material segregating to the center of the furnace. The hot gases naturally seek the lines of least resistance, and the principal reaction is up through this more open center, with a corresponding slower movement of the finer and more compact material along the side walls. With the coarser materials segregating next the side walls, the more violent reactions are next the brick work, with a cold column in the centre, and the condition is sometimes called pillaring. If the latter condition becomes localized, the action of the stock and the hot gases soon cut away the walls adjacent to the area affected, if the condition continues for any length of time. Eventually, this may develop a hot spot, showing on the shell. By the generous use of water sprayed against the hot spot the furnace can sometimes be kept in operation for a considerable length of time after a hot spot shows. In either case the colder material from the inactive zone causes a cold hearth and poor quality of iron.

Loss of Tuyeres and Chilled Hearth may be brought about by burning out the coolers due to failure of the water and by filling during a slip. Bad slips always throw a great deal of the molten slag up into the tuyeres, blowpipes and tuyere stocks where it immediately solidifies, necessitating a shut down. The large amount of comparatively cold stock that drops into the hearth from a severe slip may lower the temperature of the molten iron and slag below the fusion point, thus producing a **chill** in the hearth. When the tuyeres are finally opened in case of a bad chill, and the furnace is on blast, if necessary, before the tap hole can be opened, the iron can be tapped through the cinder notch after the removal of the coolers.

Uncertainties and Variables in Furnace Control: Besides the irregularities just mentioned which affect the furnace and occur in it, there are many others which may arise from outside sources, because to obtain uniform working of the furnace it is necessary that all the raw materials, the limestone, the coke, the ore, and the air, be kept uniform, a feat that is manifestly impossible. Again, the furnace plant may be looked upon as a composite mechanism containing many vital parts, of which the furnace itself is but the central figure. The prolonged failure of any one of these parts, the boiler plant, the blowing engines, the pumping station,

the gas mains, the water lines, or the stoves, is sufficient to close down the furnace. All of these things are of great interest to the furnaceman, but their discussion cannot be undertaken in as brief a discourse as the present one is intended to be.

Banking: Whenever it becomes necessary to close down a furnace temporarily, it is **banked.** This is done by charging coke blanks, beginning a few hours before banking. The amount of the blanks varies with the time the furnace is to be off. After the blanks have been charged, the furnace is drained as "dry" as possible of iron and slag, the connections to the rest of the plant are closed, the blast is shut off, the blow pipes and the tuyeres are removed, and the openings are bricked up tight. The bleeders, explosion doors and then the bells are opened, and the gas is allowed to pass out at the top. The furnace may now remain inactive for several days or weeks. In starting up, the furnace is filled up with coke and a little ore, the ashes are raked out through the tuyere openings, the tuyere connections are made, and the blast is turned on. The same precautions with regard to gas must be observed here as in blowing in. A week or more, depending upon the length of the banking period, may be required for the furnace to return to normal condition.

Blowing Out: In blowing out, charging is merely stopped and the stock is allowed to settle. Streams of water are allowed to flow into the try holes to keep the top cool and prevent warping of the bells. As soon as the stock line descends near the tuyeres, the blast is taken off, the tuyeres are removed, and the rest of the stock is later removed with shovels. This done, the career of the furnace is ended.

SECTION VIII.

THE BLAST FURNACE BURDEN.

Burdening the Furnace: The amounts of ore and stone charged per ton (or other fixed quantity) of fuel is referred to as the burden, the fuel or coke being constant in amount. Any increase in ore and stone above the normal is spoken of as a **heavy burden,** while the reverse of this results in a **light burden.** The regulation of the proportions of ore, flux and coke is called **burdening.** It has two objects; namely, the most efficient operation of the furnace and at the same time the production of the grade of metal desired. The subject is of the greatest importance in the operation of a furnace, and is a problem that may be solved either by practical experience or by calculations based on theoretical considerations. With a furnace well started and on familiar materials, practical knowledge only

may be required to operate successfully. But in dealing with unknown materials, theoretical burdening based on chemical analysis must be resorted to. A full discussion of these matters would make this Chapter too technical for the purpose it is intended. However, as illustrating the problems that confront the blast furnace operator, the following will supply concrete examples:

Given: A furnace with a certain capacity and raw materials of the composition shown in the following table:

Required: 1. To produce 1 ton (2240 lbs.) pig iron with every 2000 pounds coke consumed, or less.

2. To produce metal containing silicon, less than 1.25%; sulphur, less than .040%; manganese, as high as possible; carbon and phosphorus, not specified.

To determine: 1. In what proportions the ores shall be mixed.

2. Weight of ore mixture in the charge.

3. Weight of flux in the charge.

Table 27.* Analysis of Raw Materials Used in the Blast Furnace.

ELEMENTS AND RADICALS	Formula	ORES				Limestone	Coke
		1	2	3	4		
Dry Basis		%	%	%	%	%	%
Silica	SiO_2	6.48	9.04	12.78	5.86	3.43	4.40
Iron	Fe	56.80	54.84	52.93	55.59	.30	1.35
Manganese	Mn	1.14	1.09	.83	.16	.08	.07
Phosphorus	P	.082	.096	.083	.618	.006	.030
Alumina	Al_2O_3	3.22	2.70	3.34	3.63	.86	2.80
Lime	CaO	.11	.18	.25	1.22	51.45	.25
Magnesia	MgO	.14	.26	.21	.87	1.66	.15
Fixed Carbon	C	.....	.....	.....	.....	.....	90.00
Carbon Dioxide	CO_2	.....	.....	.....	.....	41.43	.....
Sulphur	S	.....	.....	.....	.....	.....	.940
Sulphuric Anhydride	SO_3	.03	.04	.04	.06	.060	Undetermined
Alkalies	Na_2O-K_2O	Trace	Trace	Trace	Trace	Trace	Trace
Titania	TiO_2	.018	.009	.012	.019	Trace	Trace
Water, (Wet Basis)	H_2O	14.06	14.50	15.00	12.10	.50	1.50

*N. B. The preceding table is intended to give a complete list of the elements and radicals which make up the solid materials entering the furnace, or the charge. The gases, i. e., the blast, may be looked upon as a mixture of oxygen and inert gases composed mainly of nitrogen. In this mixture the oxygen content is 20.8 per cent. by volume or 23.2 per cent. by weight.

Outline of a Method for Solving a Burdening Problem: In a general way the solution of the problem is arrived at in the following manner: From the physical condition of the various ores and the amount of each on hand, their relative cost or other considerations, the furnaceman first decides the approximate proportions in which it is desirable to use the ores. From these proportions he is able to determine the average composition of the ore mixture in each charge, the size of which he has also decided upon. From this average he is able to calculate the amount of ore required to produce one ton of pig iron, and the weight of the impurities therein. Then, since he must make one ton of iron with one net ton of coke, or less, he is able to arrive at the total impurities in the ore and coke required to produce one ton of iron. These impurities, he separates into acids and bases, and then combines them according to the slag ratio of acid to base which experience has taught is the best to produce the kind of iron desired. This process gives the excess acids which must be fluxed with limestone. From the analysis of the stone he determines the available base, from which the amount of limestone required to flux the excess acids in accordance with the accepted ratio can be found. The next thing to consider is the slag volume, or the amount of slag to be made per ton of iron, which experience has taught must be within certain limits to be consistent with good furnace practice. If the volume of slag is very low, its ability to remove sulphur from the iron may be seriously interfered with, while if it is very high, the fuel consumption will increase above that desirable, because coke must be consumed to furnish the heat necessary to form and fuse the slag. If the slag volume falls outside the limits which the furnaceman's judgment from experience has set for it, he must begin all over again, starting with a different mixture of ores, or different limestone or coke. Evidently, with new materials the solution of the problem involves a great deal of try-work with different combinations of the materials that may be available.

The Burden Sheet: During the operation of a furnace, the burden may be changed from time to time to meet the ever changing conditions. These changes are governed by observation and by the analysis of the pig iron and slag produced. An accurate record is kept of all changes made, and of the weights and analyses of all materials charged, and for purposes of record and of comparison between the theoretical and actual conditions, this data is all assembled at certain times, usually once each week, placed on a burden sheet, and the theoretical amounts of the various ingredients of the raw materials and the products are calculated. To illustrate the calculations involved, the following burden sheet is appended. The figures given are based on a single charge instead of on amounts of materials used for any given length of time, otherwise they represent actual conditions and show a typical charge for a furnace making basic iron. In studying the sheet it should be kept in mind that only the weights of the ores, cinder, scale, scrap, coke and stone, together with their analyses, and the theoretical analyses of the pig iron are given to

Blast Furnace Burden Sheet

Material	%	Lbs.	IRON %	IRON Lbs.	SILICA %	SILICA Lbs.	ALUMINA %	ALUMINA Lbs.	LIME %	LIME Lbs.	MAGNESIA %	MAGNESIA Lbs.	PHOSPHORUS %	PHOSPHORUS Lbs.	MANGANESE %	MANGANESE Lbs.	SULPHUR %	SULPHUR Lbs.
Ore—No. 1	53.26	15 978	49.80	7 957.044	5.8	926.724	3.0	479.340	.2	31.956	.2	31.95	.068	10.865	.77	123.031	.010	1.598
Ore—No. 2	5.51	1 653	46.80	773.604	8.2	135.546	2.3	38.019	.2	3.306	.2	3.31	.064	1.058	1.12	18.514	.062	1.025
Ore—No. 3	26.31	7 893	47.00	3 709.710	10.6	836.658	2.3	181.539	.2	15.786	.2	15.79	.078	6.157	.65	51.305	.014	1.105
Ore—No. 4	3.42	1 026	53.30	546.858	3.2	32.832	2.3	23.598	.1	1.026	.2	2.05	.072	.739	.43	4.412	.016	.164
TOTAL ORE	88.50	26 550																
Cinder, Scale, Scrap, etc.	11.50	3 450	61.25	2 113.125	7.9	272.550	1.3	44.850	1.5	51.750	.4	13.80	.155	5.348	.59	20.355	.112	3.864
TOTAL—MIX	100.00	30 000	50.33	15 100.341	7.3	2204.310	2.6	767.346	.3	103.824	.2	66.90	.081	24.167	.73	217.617	.026	7.756
Coke	51.68	15 505			5.3	821.765	3.1	480.655	.3	46.515	.2	31.01	.021	3.256			.921	142.801
Stone	25.78	7 733			2.7	208.791	1.5	115.995	51.5	3982.495	1.3	100.53	.031	2.397			.070	5.413
Dolomite																		
TOTAL CHARGE						3234.866		1363.996		4132.834		198.44		29.820		217.617		155.970
Reduced						341.791								29.820		145 078		4.819
Slagged						2893.075		1363.996		4132.834		198.44				72.539		151.151

PIG IRON PRODUCED

	THEORETICAL Pounds	THEORETICAL %	ACTUAL %
Fe	15 100.341	94.00	
Si	160.642	1.00	1.25
S	4.819	.030	.030
P	29.820	.185	.158
Mn	145.078	.903	1.03
TOTAL	16 064.2	100.000	

TOTAL TONS PRODUCED

SLAG PRODUCED

	THEORETICAL Pounds	THEORETICAL %	ACTUAL %
SiO_2	2 893.075	32.70	33.82
Al_2O_3	1 363.996	15.42	15.71
Ca O	4 132.834	46.72	47.24
Mg O	198.440	2.24	2.03
Mn O	93.641	1.06	1.01
Fe O		.15	.15
S	151.151	1.71	1.73
TOTAL	8 846.407	100.00	101.69

PRODUCT RATIOS

Slag per Ton	1 234	Lbs.
" " "	= 55.1	%
" $\frac{CaO+MgO}{SiO_2}$	= 1.4	
Coke per Ton	= 2 162	Lbs.
Mix to Coke	= 1.93	
Stone to Mix	= 25.78	%

begin with, and that all the other figures are supplied by calculation. Also, it will be observed that the analyses of the raw materials are based on these materials in their undried, or natural, state.

SECTION IX.

CHEMISTRY OF THE PROCESS.

Methods of Investigating the Reactions of the Blast Furnace: A question, which the non-technical reader is usually much interested in, is this: What changes do these numerous ingredients of the raw materials undergo during their passage through the furnace? Now, the reactions as they take place in the furnace are beyond the reach of thorough investigation; but from a study of the chemical properties of these elements and compounds under conditions similar to those existing in the furnace and from the chemical composition of the products, which is easily obtained by analysis, together with observations made in working with the furnace, reliable conclusions as to the reactions that must bring about the various transitions may be formed. Nearly all the data necessary to this study has already been supplied. However, the following brief review of the chemical properties of the elements under furnace conditions may profitably be made. These properties are revealed by laboratory experiments properly conducted under conditions approximating those of the blast furnace.

The Functions of Oxygen and Carbon: 20.8 per cent. of the blast by volume is oxygen, which enters the furnace at a high temperature, about 530° C. (986° F.), and, coming in contact with hot coke, immediately reacts with carbon, giving off heat, thus:

(1) $C+O_2=CO_2$ (+97200 cal.).

In the presence of an excess of carbon at a high temperature, CO_2 is at once reduced to CO, and 68040 cal. are absorbed (2) $CO_2+C=2\ CO$ (—68040 cal.). The net heat, then, from (1) and (2) is 29160 cal. (+97200—68040=29160 cal.).

At moderately high temperatures the CO gas formed acts as a powerful reducing agent and will liberate heat at the same time, thus:

(3) $3CO+Fe_2O_3=2\ Fe+3CO_2$ (+8520 cal.)

—87480 cal.—195600 cal. +291600 cal.=8520 cal.

At temperatures ranging from 250° C. to 700° C. (482° F. to 1292° F.), a dull red heat, the reduction of Fe_2O_3 by CO may take place in three steps, the Fe_2O_3 being successively reduced to Fe_3O_4, FeO and finally to Fe. That the reduction of the ore in the blast furnace does take place in this way is shown by the fact that a large part (60% to 75%) of the flue dust, ejected from the top of the furnace, is magnetic, though only Fe_2O_3, may have been charged. If all three of these reactions proceed to com-

pletion, the total heat liberated and the total iron reduced would be the same as that in reaction (3) for equal weights of CO. A very interesting reaction that takes place between Fe_2O_3 and CO at low temperature is (4), in which carbon is deposited and heat is liberated thus:

(4) $2\ Fe_2O_3 + 8\ CO = 7\ CO_2 + 4\ Fe + C$ (+55920 cal.)
—391200 cal.—233280 cal.+680400 cal.

Carbon is not deposited with magnetite and CO reacting together, but it may be deposited at temperatures below 600° C. (1112° F.) by the action of metallic iron upon CO, thus: Fe+CO=FeO+C. The CO_2 formed in the preceding reactions and from the decomposition of limestone may act as an oxidizing agent, absorbing or giving off heat, as shown in reactions (5) (6) (7).

(5) Fe + CO_2 = FeO + CO (—2340 cal.)
—97200 cal. + 65700 cal. + 29160 cal.

(6) 3FeO + CO_2 = Fe_3O_4 + CO (+5660 cal.)
—197100 cal. — 97200 cal. + 270800 cal. + 29160 cal.

(7) $3Fe + 4CO_2 = Fe^8O_4 + 4CO$ (—1360 cal.)
—388800 cal. + 270800 cal. + 116640 cal.

These reactions will take place at temperatures ranging from about 350° C. to 800° C. (662° to 1472° F.), and their extent will be governed by the relative amounts of CO_2 and CO in the furnace gas, obeying, in this respect, the law of mass action. To be reducing, the volume of CO in the gas mixture must equal or exceed twice the volume of the CO_2.

Carbon alone is also a reducing agent toward oxides of iron at low temperatures (450° C. to 700° C.), but the reduction of ore by carbon alone absorbs much heat as shown by the following reactions:

(8) $3\ Fe_2O_3 + C = 2\ Fe_3O_4 + CO$ (—16040 cal.)
—586800 cal. + 541600 cal. + 29160 cal.

(9) $Fe_3O_4 + C = 3\ FeO + CO$ (—44540 cal.)
—270800 cal. + 197100 cal. + 29160 cal.

(10) FeO + C=Fe + CO (—36540 cal.)
—65700 cal. + 29160 cal.

Under proper conditions the reduction of Fe_2O_3 by solid carbon may take place in a direct way, thus:

$Fe_2O_3 + 3C = 2\ Fe + 3CO$ (—108120 cal.)
—195600 cal. +87480 cal.

At very high temperatures—say around 1500°C.—carbon in large excess may reduce manganese, silicon and phosphorus oxides, the reactions being represented thus:

(11) $Mn_3O_4 + C = 3\ MnO + CO$—Heat is absorbed.
(12) MnO+C=Mn+CO—Heat is absorbed.
(13) $SiO_2 + 2C = Si + 2\ CO$.—Heat is absorbed.
(14) $P_2O_5 + 5C = 2P + 5CO$—Heat is absorbed.

Some oxygen also enters the furnace as water vapor in the blast, where the following endothermic reaction occurs: $H_2O + C = CO + H_2$.

The hydrogen formed may do work temporarily by reacting with iron oxide and reducing it thus:—(15) $FeO+H_2=H_2O+Fe$.
But the water so formed is again decomposed as shown by the presence of hydrogen in blast furnace gas. Therefore, the net energy result from water vapor is a loss.

In this connection it should be noticed that, since carbon is the only fuel employed, the carbon-oxygen reactions must be relied upon to furnish the heat required in the process, and that only a few of these are heat producing. Reactions (1)to (4) produce most of the heat absorbed by other modes of reduction, also that required to dry the raw materials, to decompose the limestone, to flux the impurities, to melt the iron and slag, and to replace the waste. On this account they are among the most important reactions occurring in the furnace.

Behavior of Nitrogen in the Furnace: Nitrogen and the other inert gases of the air, totalling 79.2% of the blast by volume, pass through the furnace, for the most part, unchanged chemically. Since they equal in weight about six-tenths of all the other materials entering the furnace, they play an important part in heat conduction, and make a source of unavoidable heat waste. Some nitrogen, however, may react with alkali carbonates and carbon to form salts of hydro-cyanic acid.
(16)$K_2CO_3+4C+N_2=2KCN+3CO$.

This reaction explains the small amount of cyanogen, $(CN)_2$, always present in blast furnace gases.

Disposition of Manganese by the Furnace: Coming now to the metalloids that are introduced into the pig iron through reduction processes occurring in the furnace, manganese is the one most closely resembling iron in its chemical conduct. While traces of the element are found in both the limestone and the coke ash, practically all that entering the furnace is present as an ingredient of the ore, in which it occurs combined with oxygen, usually as the dioxide, MnO_2, and possibly as MnO in combination with some acid radical like SiO_2 or P_2O_5. These manganese compounds are never wholly reduced in the furnace, and the proportion of them that is so reduced depends upon the conditions of temperature and basicity of the slag. Under conditions ordinarily prevailing in the blast furnace producing pig iron, from 50 to 75 per cent. of the total amount of this element charged will be found in the pig iron, the highest proportion being obtained with high hearth temperatures and basic slags. However, a high manganese content may be obtained with lower hearth temperatures by increasing the proportion in the charge. If a high manganese iron is kept molten for some time, some of the manganese sulphide will rise to the surface, like slag, and react with the oxygen of the air, liberating sulphur as oxides. With some ores, this fact can be utilized to reduce the sulphur content of the pig iron. It cannot be utilized in all cases, for in order to obtain a material reduction of the sulphur content

the manganese content of the pig iron should exceed 2 per cent. In some irons for the foundry and all irons for open hearth purposes a high content of manganese is desirable, for reasons already given.

Action of Phosphorus in the Furnace: Phosphorus enters the furnace with the charge in the form of phosphates. At very high temperatures and in the presence of coke (carbon) these compounds are completely reduced, as shown in reaction (14). Phosphorus reacts with iron to form Fe_3P, thus: (17) $3Fe+P=Fe_3P$.

This phosphide, being soluble in iron, becomes a part of the metallic bath in the blast furnace. Hence, the phosphorus in the pig iron can be controlled only through the selection of materials.

Disposition of Sulphur in the Furnace: Sulphur is carried into the furnace mainly by the coke, though small amounts, 1 to 15 per cent. of the total, are found in the ore and the limestone. The sulphur contained in the coke enters in the form of elementary sulphur and FeS, all of which, when melted, alloys with the iron in the furnace; a smaller portion, in the form of sulphates, such as $CaSO_4$, enters as an impurity in the ore, limestone and coke, and is reduced to sulphide at a low red heat and in the presence of carbon. At a very high temperature and in the presence of a basic slag and carbon, the following reaction may take place. (18) $FeS+CaO+C=CaS+Fe+CO$. Owing to lack of proper conditions in the blast furnace, this reaction is never complete, so a small portion of the sulphur remains in combination with the iron. This iron sulphide, being soluble in iron, becomes a part of the metal.

Behavior of Silicon: Silicon enters the furnace as SiO_2, some of which may be combined with bases as silicates. At temperatures of about 1200° C. (2192° F.), corresponding to the fusion zone in the blast furnace, the greater portion of this silica combines with lime, CaO, and other bases to form silicates, which have already been discussed under the heading of slags. However, at a high temperature, such as exists in the hearth of the furnace, and in the presence of carbon, silica is reduced, and the resultant silicon combines with the iron. (19) $SiO_2+2C=Si+2CO$.

(19A) $Fe+Si=FeSi$.

Action of Calcium and Magnesium: Calcium and Magnesium enter the furnace mostly as carbonates. Small portions may be in the form of silicates, in which CaO and MgO are combined with SiO_2, and may undergo no chemical change in the furnace. The carbonates, however, are decomposed at temperatures above 800° C., liberating CO_2.

(20) $CaCO_3=CaO+CO_2$. (21) $MgCO_3=MgO+CO_2$.

At the proper temperature for their formation the caustic lime and magnesia, in intimate contact with SiO_2, will both combine with it to form slags.

Action of Aluminum: Aluminum, in the form of alumina, Al_2O_3, and alumina silicates, is found in ore, flux and fuel. Neither alumina nor its silicates are reduced under the conditions that prevail in a blast furnace. Al_2O_3, as already pointed out, may exert a marked influence upon the fluidity and fusibility of the slag.

Action of Less Abundant Elements: Titanium, potassium, sodium, zinc, arsenic, copper and chromium, are elements, a few of which are present in very small amounts in the materials used in the Pittsburgh district. Titanium enters the furnace as titania, TiO_2, combined with some base. Titania is similar to silica, SiO_2, except that it is more difficult to reduce at temperatures attainable in the blast furnace, and all but traces of it, which is found in the iron, passes out with the slag. Under the conditions prevailing in the furnace, titanium exhibits a slight tendency to combine with carbon and nitrogen to form titanium cyano-nitride. This substance is sometimes found in the salamander on the hearths of furnaces being repaired. Here, it occurs in the form of small cubes that have the appearance of copper. The alkalies, soda and potash, are found in nearly all blast furnace slags, and when they are present in the raw materials to a considerable extent, they are partly volatilized and driven over out of the furnace with the flue gases, from which they may be separated with an installation of suitable apparatus. Zinc is a very troublesome element when present in blast furnace material. Its compounds may be reduced in the lower regions of the stack; but, if so, the zinc is volatilized, driven upward by the blast, and oxidized to zinc oxide, which condenses on the walls of the colder part of the flues and in time closes up the passages to such an extent as to seriously restrict the flow of the gases. Zinc oxide also tends to combine with the alumina in the fire brick lining of the furnace, causing the brick to expand with consequent evil, or even disastrous, results. Arsenic acts very much like phosphorus. All of its compounds are reduced, and the resultant elementary arsenic then combines with iron to form iron arsenide which dissolves in the metal. Copper compounds are readily reduced, yielding metallic copper, which alloys with the iron. Chromium is separated from its oxides only with great difficulty in the blast furnace, an exceedingly high temperature and a special slag being required for the reduction of its oxides.

The Reactions Within the Furnace: With these facts concerning the properties of the various ingredients of the raw materials in mind, the changes that take place in the blast furnace are more easily understood. The accompanying chart (Fig. 59) gives a graphic representation of these changes, showing the relative weights and volumes of materials, the reactions and the temperatures at which the changes take place and the final disposition of the products. In studying this chart, however, one important fact should be kept in mind. It is this: Owing to the conditions prevailing within the furnace, very few, if any, of the reactions will be complete, that is, use up all the material at hand at the location indicated.

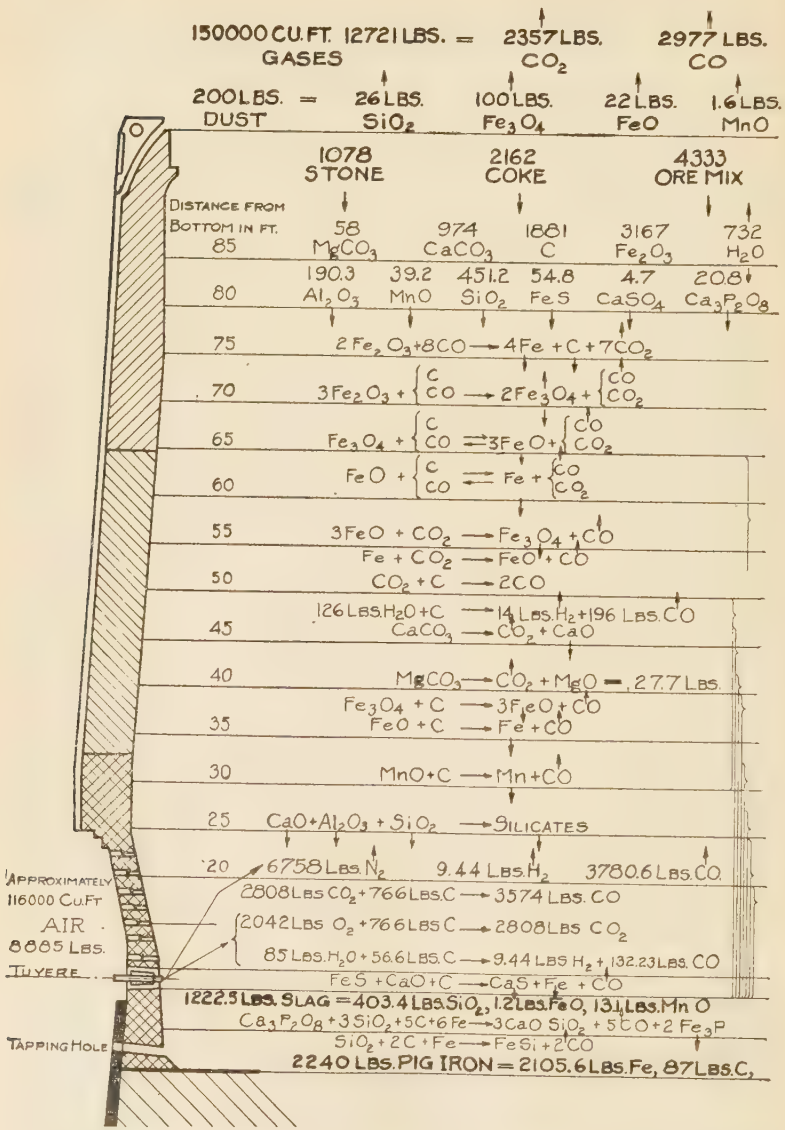
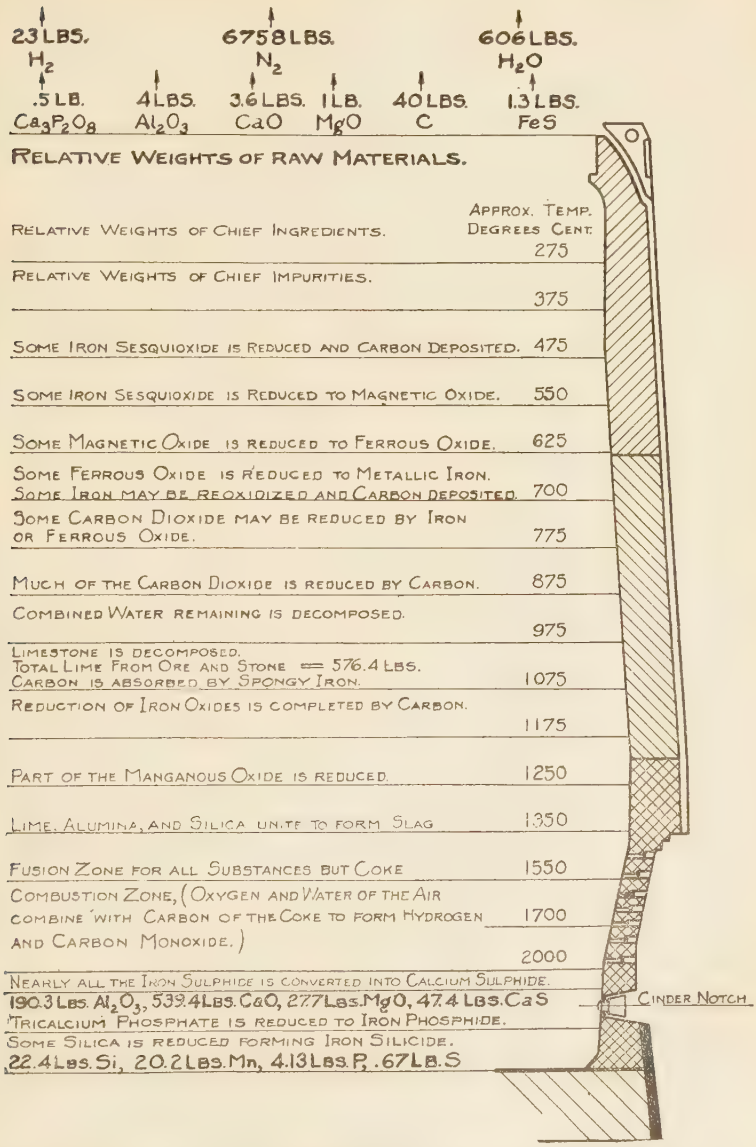

150000 CU.FT. 12721 LBS. = GASES
2357 LBS. CO_2
2977 LBS. CO
200 LBS. = DUST
26 LBS. SiO_2
100 LBS. Fe_3O_4
22 LBS. FeO
1.6 LBS. MnO
1078 STONE
2162 COKE
4333 ORE MIX
DISTANCE FROM BOTTOM IN FT.
58 $MgCO_3$
974 $CaCO_3$
1881 C
3167 Fe_2O_3
732 H_2O
190.3 Al_2O_3
39.2 MnO
451.2 SiO_2
54.8 FeS
4.7 $CaSO_4$
208 $Ca_3P_2O_8$
85
80
75
70
65
60
55
50
45
40
35
30
25
20
$2Fe_2O_3 + 8CO \rightarrow 4Fe + C + 7CO_2$
$3Fe_2O_3 + \{C, CO \rightarrow 2Fe_3O_4 + \{CO, CO_2$
$Fe_3O_4 + \{C, CO \rightleftharpoons 3FeO + \{CO, CO_2$
$FeO + \{C, CO \rightleftharpoons Fe + \{CO, CO_2$
$3FeO + CO_2 \rightarrow Fe_3O_4 + CO$
$Fe + CO_2 \rightarrow FeO + CO$
$CO_2 + C \rightarrow 2CO$
126 LBS. H_2O + C → 14 LBS. H_2 + 196 LBS. CO
$CaCO_3 \rightarrow CO_2 + CaO$
$MgCO_3 \rightarrow CO_2 + MgO$ — 27.7 LBS.
$Fe_3O_4 + C \rightarrow 3FeO + CO$
$FeO + C \rightarrow Fe + CO$
$MnO + C \rightarrow Mn + CO$
$CaO + Al_2O_3 + SiO_2 \rightarrow$ SILICATES
6758 LBS. N_2 9.44 LBS. H_2 3780.6 LBS. CO
2808 LBS CO_2 + 766 LBS. C → 3574 LBS. CO
APPROXIMATELY 116000 CU.FT AIR 8885 LBS.
2042 LBS O_2 + 766 LBS C → 2808 LBS CO_2
85 LBS. H_2O + 56.6 LBS. C → 9.44 LBS H_2 + 132.23 LBS. CO
TUYERE
$FeS + CaO + C \rightarrow CaS + Fe + CO$
1222.5 LBS. SLAG = 403.4 LBS. SiO_2, 1.2 LBS. FeO, 13.1 LBS. Mn O
$Ca_3P_2O_8 + 3SiO_2 + 5C + 6Fe \rightarrow 3CaO\,SiO_2 + 5CO + 2Fe_3P$
TAPPING HOLE
$SiO_2 + 2C + Fe \rightarrow FeSi + 2CO$
2240 LBS. PIG IRON = 2105.6 LBS. Fe, 87 LBS. C,

FIG. 59. The Making of a Ton of Pig Iron. A diagram showing the raw changes that take place therein.


23 LBS. H_2
.5 LB. $Ca_3P_2O_8$
4 LBS. Al_2O_3
6758 LBS. N_2
3.6 LBS. CaO
1 LB. MgO
40 LBS. C
606 LBS. H_2O
1.3 LBS. FeS
RELATIVE WEIGHTS OF RAW MATERIALS.
RELATIVE WEIGHTS OF CHIEF INGREDIENTS.
APPROX. TEMP. DEGREES CENT.
275
RELATIVE WEIGHTS OF CHIEF IMPURITIES.
375
SOME IRON SESQUIOXIDE IS REDUCED AND CARBON DEPOSITED. 475
SOME IRON SESQUIOXIDE IS REDUCED TO MAGNETIC OXIDE. 550
SOME MAGNETIC OXIDE IS REDUCED TO FERROUS OXIDE. 625
SOME FERROUS OXIDE IS REDUCED TO METALLIC IRON.
SOME IRON MAY BE REOXIDIZED AND CARBON DEPOSITED. 700
SOME CARBON DIOXIDE MAY BE REDUCED BY IRON OR FERROUS OXIDE. 775
MUCH OF THE CARBON DIOXIDE IS REDUCED BY CARBON. 875
COMBINED WATER REMAINING IS DECOMPOSED. 975
LIMESTONE IS DECOMPOSED.
TOTAL LIME FROM ORE AND STONE = 576.4 LBS.
CARBON IS ABSORBED BY SPONGY IRON. 1075
REDUCTION OF IRON OXIDES IS COMPLETED BY CARBON. 1175
PART OF THE MANGANOUS OXIDE IS REDUCED. 1250
LIME, ALUMINA, AND SILICA UNITE TO FORM SLAG 1350
FUSION ZONE FOR ALL SUBSTANCES BUT COKE 1550
COMBUSTION ZONE, (OXYGEN AND WATER OF THE AIR COMBINE WITH CARBON OF THE COKE TO FORM HYDROGEN AND CARBON MONOXIDE.) 1700
2000
NEARLY ALL THE IRON SULPHIDE IS CONVERTED INTO CALCIUM SULPHIDE.
190.3 LBS. Al_2O_3, 539.4 LBS. CaO, 27.7 LBS. MgO, 47.4 LBS. CaS
TRICALCIUM PHOSPHATE IS REDUCED TO IRON PHOSPHIDE.
SOME SILICA IS REDUCED FORMING IRON SILICIDE.
22.4 LBS. Si, 20.2 LBS. Mn, 4.13 LBS. P, .67 LB. S
CINDER NOTCH

materials and the products of the blast furnace; their relative weights and the

Thus, the first reaction, showing the reduction of the ore to metallic iron with the deposition of carbon, affects only a part of the ore and gas. This condition, with but one exception, holds for all these reactions. Even limestone, which will decompose completely into lime and carbon dioxide at 1000° if given sufficient time, will often reach the tuyeres as calcium carbonate. The fact that iron and manganese oxides are not completely reduced is established by their presence in the slag. The one exception to this rule is phosphorus. Its compounds, down to small traces, are completely reduced.

The explanation for these statements is to be found only in a careful study of chemical laws in connection with the conditions prevailing in the furnace. Such a study reveals the fact that the reactions in the upper part of the stack of the furnace are subject to conflicting tendencies. Thus, there are in constant contact with the solid substances, Fe_3O_4, FeO, Fe, and C, the gaseous substances, CO and CO_2. Of these, Fe_3O_4 and CO_2 are oxidizing agents. FeO and CO may act as either oxidizing or reducing agents, while C and Fe are reducing agents. With these substances in contact at any given temperature and in any given proportions as shown on the chart, the reversible reactions would proceed in a given direction until equilibrium should be established, and no further change would occur until either the concentration of one of the reacting substances or the temperature should change. Then the reactions, subject to the law for mass action, would proceed in a direction that would again establish equilibrium. But the slow downward movement of the stock to regions of higher and higher temperatures, the presence of an excess of carbon and the rapid upward flow of the gases, which has the effect of giving a constant surplus of CO and of carrying CO_2 out of the field of action, tend to prevent the establishment of equilibrium, and to force the reactions to proceed in a direction that results in the final reduction of the iron oxides, with the consequent oxidation of either the C or the CO. These same conditions, however, which tend to reduce the oxides of iron, prevent the complete oxidation of the CO to CO_2, because the CO, passing so rapidly over the stock, does not have time to become wholly oxidized, and the presence of the reducing agents, Fe, FeO, and C, tends to oppose the formation of CO_2. The escaping top gases, therefore, always show a large content of CO, much in excess of the CO_2 content. In modern furnaces, operating according to the prevailing practice with respect to coke consumption, the relative volumes of CO and CO_2 are approximately 2 to 1. In the lower part of the stack, the temperature is so high that CO_2 can exist but momentarily in the presence of carbon, and any oxide reduced in this region results in the gasification of a proportionate amount of carbon. This direct reduction of oxide by carbon is the most inefficient mode of reduction, because it absorbs much heat, as shown by reactions (8), (9), and (10), and robs the tuyeres of carbon needed for combustion. This mode of reduction, then, is one the furnaceman strives to avoid so far as possible.

Tracing the Materials Through the Furnace: The ore, limestone and coke, upon being charged into the top of the furnace, come in contact

with an ascending current of hot gases (temperature about 275° C.). The first change that takes place is the physical one of drying. The hygroscopic water, being first driven off and carried out of the furnace by these gases, is then followed by the water of crystallization. The stock, with its interstitial spaces filled with an ascending atmosphere containing the reducing gas CO, starts to descend toward the bottom of the furnace and to regions of higher and higher temperatures. At different levels, then, chemical reactions peculiar to the temperatures of these levels will occur. At first only the oxides of iron and carbon suffer change, and the first reaction to occur is number (4), in which carbon deposition takes place at a temperature as low as 300° C. A large part of the remaining iron oxide, in the presence of both C and CO, is next reduced in successive levels and temperatures as follows:

$$3Fe_2O_3+\begin{cases}C\\CO\end{cases}=\begin{cases}CO\\CO_2\end{cases}+2Fe_3O_4, \text{ begins at } 450^\circ \text{ C.}$$

$$Fe_3O_4+\begin{cases}C\\CO\end{cases}=\begin{cases}CO\\CO_2\end{cases}+3FeO, \text{ complete at } 600^\circ \text{ C.}$$

$$FeO\ +\begin{cases}C\\CO\end{cases}=\begin{cases}CO\\CO_2\end{cases}+Fe, \text{ begins at } 700^\circ \text{ C.}$$

At about 800°C. the free iron is subject to re-oxidation by CO_2, as are also the compounds FeO and Fe_3O_4 though to a less degree, the chief action being represented by reaction (5). At 800° C., or a little above, the decomposition of limestone takes place, thus: $CaCO_3=CaO+CO_2$. This reaction is complete at 1000° C. At 900° C., carbon reduces CO_2 to CO, thus: $C+CO_2=2CO$, so that CO_2 does not normally exist below the 60 foot level. From this level the mixture is one of gangue, quick lime, coke, spongy iron and varying amounts of unreduced ore, all of which descend to the fusion zone with very little change, if the absorption of carbon by the iron and the action of carbon on the unreduced ore be excepted. At this level, which is located at the top of the bosh, the lime combines with some of the gangue and, with a little unreduced iron oxide and manganese oxide, forms a part of the slag. The slag, such as is already formed, and the iron, both now in the liquid state, trickle down through the interstices of the coke to the hearth, where they become separated by gravity, forming these two layers; a lower or metallic layer containing all reduced substances and an upper or slag layer containing all unreduced matter. Here, since these two layers are in contact with each other and with carbon of the coke, which probably extends to the bottom of the hearth, or at least to within a few inches of the bottom, reactions (11), (12), (13), (14), (17), (18), and (19), known as hearth reactions, occur.

Conditions Affecting the Amount of Silicon and Sulphur in the Metal: Reactions 13 and 18 should receive special attention here, because of all the reactions that directly affect the quality of pig iron, these are the only ones the furnaceman can control. Number (13), $SiO_2+2C=Si+$

2CO, depends upon two conditions, namely, temperature and basicity of slag. High temperatures favor the reaction, while basic conditions of the slag retard it. Reaction (18), $FeS+CaO+C=CaS+Fe+CO$, is subject to the former influence only. Therefore, the conditions which tend to raise the silicon content of the iron will lower the sulphur, provided the high temperature is obtained without the use of an excessive amount of high sulphur coke. In both these cases, the extent to which the reactions will progress under any given set of conditions, is governed by time. The longer the time the farther they will progress. This fact results in a difference in composition between the first and last metal in the same cast. Since the iron on the bottom of the furnace crucible is formed four or five hours before that on the top of the layer at the time of tapping, these reactions will tend to advance farther in the first than in the last iron formed under normal conditions. The first of the cast will, therefore, usually be found to contain a higher percentage of silicon and a lower percentage of sulphur than the last. This first iron is called "hot iron" on this account, because, as will be shown later, the oxidation of the silicon generates heat, when the pig iron is purified, as in the Bessemer process for the making of steel.

CHAPTER VII.

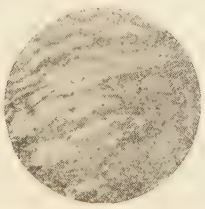
THE MANUFACTURE OF WROUGHT IRON

SECTION I.

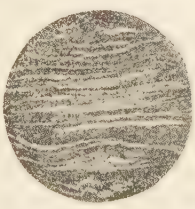
HISTORY OF METHODS FOR PRODUCING WROUGHT IRON AND STEEL.

Definitions: Wrought iron can only be defined as a variety of commercially pure iron, which is produced by some process, or processes, whereby the metal is obtained in a pasty condition. It cannot be considered as pure iron nor as the purest form of commercial iron, for dead-soft steel produced by the basic open hearth process carries as small a content of total impurities as is found in a great deal of wrought iron, and one brand of an open hearth product, sometimes spoken of as ingot iron, uniformly contains a smaller percentage of total impurities than the purest and best grades of wrought iron. (See Table 28, p. 209.) It cannot be said to be the product of any particular process, because, as will be shown in what is to follow, it has been produced in many different ways. However, by whatever process, it is always obtained in a pasty, or semi-fused condition, and in masses, or bodies, composed of cohering granules partially surrounded by slag. In mechanically working these sponge-like masses, the granules of metal are elongated and more or less welded together, while a large portion of the slag is squeezed out of the mass and the rest remains as threadlike but irregular masses intermingled with the iron.

Tests for Wrought Iron: On account of this fact, wrought iron is characterized by a fibrous structure, which can be readily seen by nicking a bar on one side and bending it double. This fibrous structure may also be revealed by filing the bar, or other article, transversely—the filing test,—or, better, by means of the etching test. In this latter test, the surface to be tested, usually a cross section, is first filed or ground smooth, then polished; and the etching medium is applied until the structure is fully developed.



SINGLE ROLLED OR REFINED



DOUBLE ROLLED OR DOUBLE REFINED

FIG. 60. Structure of Slab-piled Wrought Iron Bars. Cross sections of 1-inch rounds. Natural size, etched with tincture of iodine.

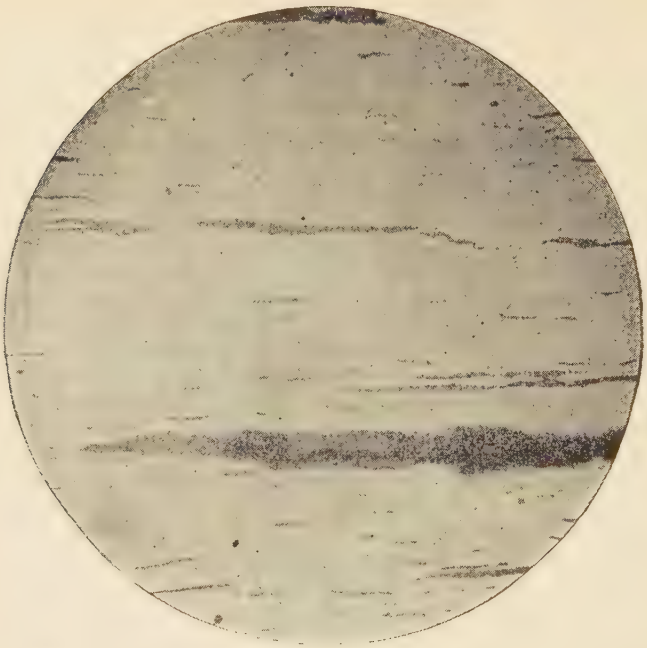


FIG. 61. Slag in Wrought Iron. Longitudinal section of double refined bar. Unetched and magnified 100 diameters.

The etching medium is usually composed of 1 part hydrochloric acid, 1 part sulphuric acid and 6 parts water, though ordinary tincture of iodine is preferred by some. As soon as the structure has become fully developed, the surface is washed two or three times with alcohol, and then quickly dried in order to prevent rusting. These are the most reliable tests for wrought iron; chemical analysis alone is not sufficient to identify it. The accompanying cut (Fig. 60) shows the structure as developed with tincture of iodine. It should be remembered, however, that the fibrous structure is not always of the straight, striated form shown in this figure, for it may be greatly distorted and rendered very irregular by varying the manner of working the material. This fact will become evident from the descriptions to be given later.

Direct Processes of Producing Wrought Iron and Steel: Prior to the introduction of the blast furnace, which originated in Central Europe sometime before the year 1340, and probably for many years thereafter, wrought iron was wholly produced direct from the ore. Direct methods are still in use among certain uncivilized people, and, indeed, have never been wholly abandoned by the most advanced nations. The case with

which iron ores are reduced makes the direct process appear enticingly simple and logical. The reduction takes place at low temperatures and absorbs little heat, for some of the reactions are actually exothermic. The difficulty lies in the fact that the iron so obtained is in a finely divided state—**sponge iron**—and in this condition it oxidizes readily, so readily, in fact, that it may be ignited in air from the heat of a match. In order that the sponge iron may be agglomerated into a mass that can be worked, it must be heated to a temperature sufficiently high for welding or melting and be protected meanwhile from the air or other oxidizing gases.

Table 28. Showing Composition of Various Grades and Kinds of Iron All Produced from about the Same Grade of Pig Iron.

KIND OF METAL	Representative Chemical Analysis						Approximate[1] Physical Properties			
	% C	% Mn	% S	% P	% Si	% Oxides and Slag	Tensile Strength	Elastic Limit	Elongation 8 in.	Reduction of Area
Pig Iron (coke)	3.85	.90	.025	.586	.95		Weak and Brittle.			
Refined Iron, Running Out Fire	3.50	.05	.024	.390	.20	None	Very Brittle.			
Charcoal Knobbled Iron	.04	.04	.014	.045	.01	.92	45000	29000	35	60
Double Refined Puddled Iron	.02	.05	.025	.110	.12	2.00	48500	33000	28	48
Basic Open Hearth "Ingot Iron"	.02	.05	.030	.010	.01	None	41000	28000	36	70
Basic Open Hearth "Dead Soft" Steel	.08	.35	.035	.015	.01	.002	51000	31000	34	62

[1]The terms used in measuring the physical properties are fully explained in Chapter I, Part II of this book.

Early Methods of Carrying on the Direct Process: In view of the centuries the direct process was used, it is to be expected that many different methods and types of apparatus would be developed. Little is known of the furnaces in use prior to the eighteenth century, but they were for the most part of the hearth type, while the remainder were of shaft type and may be compared to small blast furnaces. While these furnaces might, and did, differ widely as to form, size and materials of construction, the fundamental metallurgical principles were the same in all. The ore, in more or less finely divided form, was charged into the furnace mixed with charcoal, which served the triple purpose of a fuel,

a reducing agent, and a protector to shield the metal reduced from the oxidizing influences of the air. In the more recent models of these furnaces, combustion of the charcoal was accelerated by means of an air blast from a bellows. The Catalan forge originally made use of a water blower, or trompe, for producing the blast. In this device water was allowed to fall vertically through a hollow wooden pipe, about 30 feet long, which contained several small holes near the upper end. The water thus aspirated air down the tube into a wooden chamber, from which the air was driven through an opening in the top to a tuyere and into the furnace, while the water escaped through a smaller opening in the bottom.

The American Bloomery, which represented the highest development in the hearth type of furnace, was provided with water cooled metal sides and a hot blast obtained by passing the air about cast iron pipes through which the hot gases passed from the furnace to the stack. The bellows supplying the blast was operated by a water wheel or steam engine. These hearths, rectangular in shape, were about 2 feet deep and 3 feet wide, and were provided with a chimney for carrying off the waste gases. Usually, they were open in front like an open fire place, with the tuyere placed either at one side or at the back, about 20 inches above the bottom. Charcoal was first put into the hearth, the blast turned on, and when the fire was burning well, some ore was spread on the charcoal. Thereafter, charcoal and ore were added alternately until a sufficient amount of metal had collected upon the bottom. Then the iron, in a pasty mass and mixed with much slag, was removed from beneath the fuel bed with bars and tongs and hammered into a bloom. The last iron to be produced by the bloomeries in this country was made in 1901.

Shaft Furnaces were used principally in Sweden and India. They consisted of an enclosed hearth surmounted by a vertical shaft which served both as a stack and a channel for charging the charcoal and ore. The ore was reduced in the stack, and the sponge iron was thus surrounded by an atmosphere of carbon monoxide until it reached a point near the tuyere just above the bottom, where it was heated hot enough to become pasty and agglomerated to some extent. When iron had thus collected up to the level of the slag hole, charging would be stopped and one side of the bottom of the furnace would be torn out for the removal of the ball.

Later Methods For Carrying on the Direct Process: From 1850 up to the present time, many attempts have been made to develop a direct process that would be practicable and able to compete with the indirect processes for manufacturing wrought iron and steel. These attempts have embraced practically every known type of apparatus suitable for the purpose, including reverbatory furnaces, regenerative furnaces, shaft furnaces, retort furnaces, electric furnaces, and various combination furnaces. Various kinds of reducing agents have also been tried, including coal, coke, graphite, distillation residues, producer gas, coal gas, and

water gas. As practically all of these processes have been abandoned, it is deemed unprofitable to include details of them all here, especially since adequate descriptions are to be found in other works on this subject.[1]

The Lang Process, patented in the United States in 1920, represents one of the more recent attempts at a direct method for producing ingot iron or steel commercially. From a description by the patentee[2], the process is carried out as follows: Pulverized iron ore is thoroughly mixed with a carbonaceous fuel and placed, along with the requisite fluxing materials, within iron retorts or shells which are preferably spherical or cylindrical in form and contain a number of small holes for the escape of gases. These retorts are then charged into the cooler end of a long continuous type of heating furnace, supplemented by a high-temperature, or melting compartment, at the hot end. As the retorts roll slowly down the inclined bottom of the reducing furnace, they are gradually heated to a bright red and kept at this temperature for 6 or 8 hours, during which time the ore is reduced and the resulting iron left in sponge form or sintered into a porous mass. This furnace is heated partly by an independent fire at the hot end and partly by the combustion of the gases evolved from the retorts. When the retorts have reached the lower and hotter end of the reducing furnace, or compartment, the door separating the two compartments is raised, and the retorts are allowed to roll into the melting compartment where the retorts and their contents are rapidly melted, the gangue being separated from the metal as a slag. The melting compartment may be a gas fired regenerative furnace, similar to an open hearth, or an electric furnace. Since the process, up to this point, is practically continuous, the melting compartment cannot be used for finishing the metal, which is, therefore, periodically tapped into a ladle and transferred to an auxiliary furnace, where it may be brought to the composition desired and heated to the proper temperature for casting into ingots. No reliable data as to the cost of the process is given, as the largest heats made up to the time this article was written had not exceeded two tons.

Present Status of the Direct Processes: While the problem of producing iron and steel direct from the ore is a very attractive one and appears more logical than the indirect processes, in which pig iron is first produced and then purified to make wrought iron and steel, the fact remains that, notwithstanding it was the original process and in spite of the many attempts to keep it in use, it has failed hopelessly in economic competition with the indirect methods. While one or more drawbacks may be cited for the failure of each of these attempts, and many reasons may be cited for the failure of the direct process to hold its own, it would

[1]See, Iron and Steel, by Hugh P. Tiemann; McGraw-Hill Book Co., New York; The Metallurgy of Iron and Steel, by Thomas Turner; J. B. Lippincott Co., Philadelphia; Metallurgy of Steel, by H. M. Howe, McGraw-Hill Book Co., New York.

[2]See, The Iron Age, Vol. 107, No. 19 (May 12, 1921).

appear that the chief reasons why it resists all efforts to revive it are these: 1. The ore must be a very rich one. 2. The ore must be finely divided and intimately mixed with the reducing agent. 3. So far, no practical plan has been evolved whereby the ore and reducing agent may be mixed in proper proportions to leave no excess of either. If an excess of the former is permitted, the process is wasteful of ore, while in the presence of an excess of the latter, the iron must be obtained at a low temperature in sponge or pasty form hard to handle, else, at a higher temperature, the phosphorus will be reduced and carbon will be absorbed, giving a very impure metal little better than pig iron. 4. Sulphur is readily absorbed by the metal, but it cannot be removed except under highly reducing conditions such as prevail in the blast furnace or an electric furnace, and, except the conditions are most favorable, the electric furnace is still an expensive instrument for the purification of iron.

Indirect Methods for Producing Wrought Iron: Just how, when, where and by whom wrought iron was first produced from pig iron is unknown, though it is probable the process originated in Belgium. The first attempts were doubtless made in the forge or on a hearth such as those already described for the production of wrought iron directly from the ore. Here the action of the air from the blasts, by that time in general use, would, if the iron were properly handled during the heating, result in the oxidation of the silicon and the greater portion of the manganese and carbon, giving a ductile and workable product. The first hints we have of the process from written records date from about 1620, but by that time the process had reached a stage of considerable development. Previous to that date, the Walloons of Flanders had gone to Sweden, where they had introduced the process, since known as the Walloon process. In this process a rather deep hearth with one or two tuyeres was used. With the hearth filled with charcoal and heated to a high temperature, the pig iron, in the form of long pigs, was fed into the fire with tongs, so that the lower end of the pig would be gradually melted, and the molten metal would trickle to the bottom directly in front of the blast. The metal, thus desiliconized and decarbonized by the air, would collect as a pasty mass upon the bottom, whence it would be removed as desired, and worked. The pig used, since it was reduced from the famous Dannemora ore in charcoal furnaces, was exceptionally low in silicon, sulphur and phosphorus, hence was especially adapted to this process.

Two-Stage Processes: Few districts outside of Dannemora are favored with ore so free from phosphorus, while the use of coke in the blast furnace leaves no alternative but the production of high silicon iron, for if the temperature is lower, a condition necessary to produce low silicon iron, the sulphur content will be increased. Such iron could not be purified in a single operation, as in the Walloon process, where the purification was carried on in the combustion chamber with the metal and slag in contact with the solid fuel. It was found, however, that this iron could

be purified and converted into wrought iron very readily in two stages. For the first stage a small rectangular water-cooled hearth surmounted by a stack and provided with a number of tuyeres, was used. With a good fire burning upon the hearth, alternate charges of coke and pig iron were made upon it. As the metal melted, it would collect upon the bottom of the hearth where the blast from the tuyeres impinged upon it, oxidizing the silicon and some of the phosphorus along with a part of the iron. When a sufficient quantity of metal had thus collected in the hearth, it was tapped and transferred to another hearth, fired with charcoal. Here the metal, while exposed to the blast, was constantly agitated with an iron paddle, which treatment promoted the oxidation of the carbon. As the carbon was being removed, the metal gradually assumed a pasty condition, when it was worked into a ball, taken from the furnace, and hammered. These two hearths were known by various names. The first was called the refinery, or refinery fire, if the metal tapped was allowed to solidify, or, if the metal was allowed to flow directly into the second hearth, as the melting finery or running-out fire. The second was known as the finery, charcoal finery, or more often, knobbling fires. In the Lancaster process, largely used in the United States and Sweden, the finery hearth was supplemented by a second chamber, or hearth, a little above the first, so that, by the use of charcoal for fuel, both stages of the process could be carried out in the one furnace.

Puddling Processes: About 1613, Rovenson invented the reverberatory furnace, which he described as a bloomery, finery or chaffery "of division in which the material to be melted or wrought may be kept divided from the touch of the fuel,"[1] but it was not employed for purifying pig iron until 1766, when the Cranege Brothers received a British patent on a process which later came to be known as puddling. With careful manipulation, they were able to convert white iron, or refined iron, placed upon the bottom of a reverberatory furnace, into a good malleable iron by the use of raw coal alone for fuel. In 1784, Henry Cort hollowed out the bottom of the furnace so as to contain the metal in the molten state, then by agitating this "puddle" or bath of metal with an iron bar or paddle he was able to convert white, or refined, iron into a malleable iron, the carbon being burned out by the oxidizing gases of the furnace atmosphere.

As the furnace bottom was made up of sand, it was rapidly fluxed away by the iron oxide formed. Besides, the process consumed much time and was wasteful of iron, the yield being less than 70 per cent. of the metal charged. These objectionable features were largely overcome by Joseph Hall, who, in 1830, substituted old bottom material for the sand, thus introducing the oxide bottom, which adapted the process to any grade of iron, shortened the time of the heats, and increased the yield to about

[1] Chronology of Iron and Steel, by Stephen L. Goodale and J. Ramsey Speer, published by Pittsburgh Iron and Steel Foundries Co.

90 per cent. On account of the ebullient action of the bath caused by the rapid oxidation of the carbon by the oxides on the bottom, Hall's process came to be known as the "pig boiling" process. Later, when this process had become the leading method for the production of wrought iron, the original method was designated as "dry puddling" because of the small quantity of slag formed, the slag forming impurities having been removed in the refinery. Hall, or his associates, also introduced the use of air-cooled iron plates for supporting the bottom and sides, which materially increased the life of the furnace. During the next 30 years, few changes were made in the process, for the new process was so far superior to previous ones that there was left little incentive for improvement. This attitude was changed, however, with the introduction of the pneumatic, or Bessemer, process in 1856. Then, in order to overcome competition of the Bessemer iron, or steel, and incidentally lessen the labour of puddling, which, like all its predecessors, was very arduous, hundreds of attempts have been made to improve and cheapen the process. Few of these attempts have been successful, and even the most promising of the successful ones have, for various reasons, chief of which is the hopelessness of competing with steel, failed of universal adoption. Consequently, hand puddling remains today as the chief method for the production of wrought iron.

SECTION II.

DETAILS OF THE PUDDLING PROCESS—CONSTRUCTION OF FURNACE AND EQUIPMENT.

Iron Works Equipment: Iron works vary a great deal in equipment and arrangement, for both depend to a considerable extent upon the products manufactured, and also upon other indefinable factors. Therefore, any attempt at specificness in this description must be abandoned for general principles. The production of any wrought iron article takes place by well-defined steps, which in general, correspond to the three principle classes of mill products, designated as:

1. Muck bar, muck iron, puddled iron, or No. 1 iron.
2. Merchant bar, refined bar, refined iron, single rolled iron, or No. 2 iron.
3. Double refined iron, double rolled iron, best bar, or No. 3 iron.

The essential equipment for the manufacture of the primitive product, muck bar, consists of a puddling furnace, or furnaces, a squeezer, and a rolling mill. For hand puddling this equipment has been practically standardized, hence will be described in detail, because such a description will aid in understanding the metallurgical principals involved and also the peculiarities of the product.

Construction of the Hand Puddling Furnace: Although various modifications have been introduced in the construction of puddling furnaces, affecting both size and design, the tendency has been to adhere to the smaller and simpler types, such as the one shown in the accompanying drawings. This type is known as a single furnace, has a capacity rating of 500 pounds per heat, and is coal fired. From the section shown at the bottom of this page, it will be observed that the furnace is made up of three parts, as follows: The grate, or fire place, located at one end of the furnace; the neck, or flue, at the opposite end, leading to the stack; and the

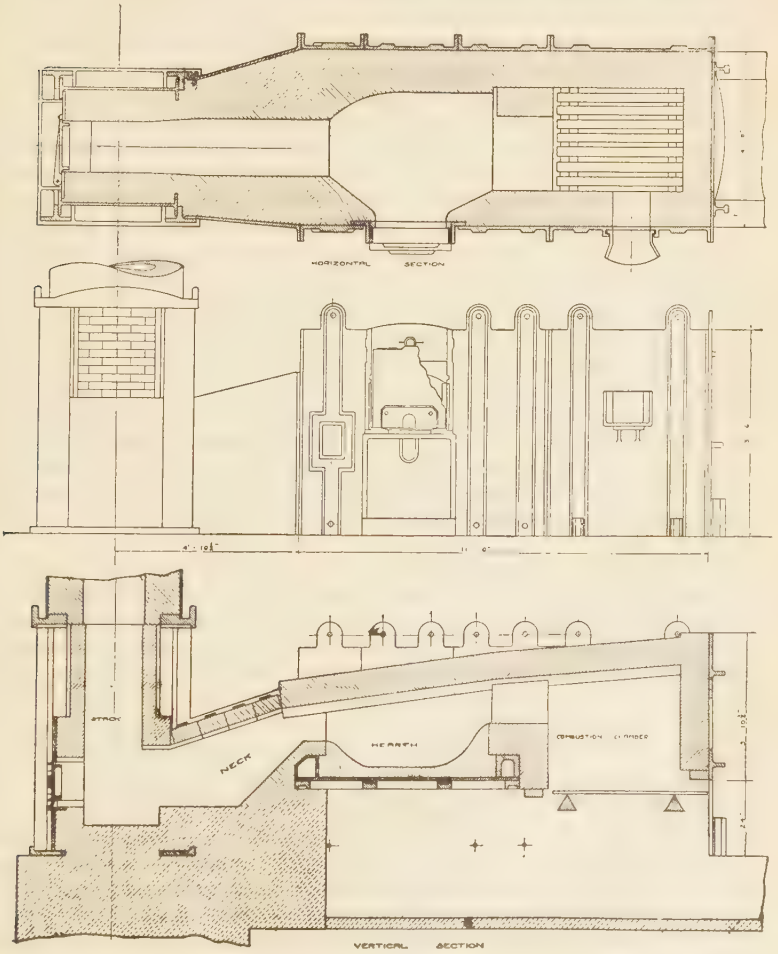


FIG. 62. Drawings Showing Plan and Sections of the Puddling Furnace.

hearth, or puddling basin, centrally located between the grate and the neck. The furnace is constructed entirely of brick, but is encased on the sides by a shell of iron plates held in place by means of tie rods. As the furnace is of the reverberatory type, all these parts are covered by an arched roof which slopes from the fire place to the up-take flue at an angle of 8 to 10 degrees. This roof is built of fire brick over the fire place, but usually of silica brick over the hearth and neck, and is about 9 inches thick.

The Fire Place, which measures about 3½ ft. in length, 2¾ ft. in width and 3¼ ft. in height at the rear, is enclosed on each side by 12-in. fire brick walls and at the rear by a 9-in. wall of the same material. At the bottom of the fire place, the space over the ash pit is bridged by two A-shaped cast iron bearers, one in front and one at the rear. Upon these bearers are placed the grate bars, made of 3 x ¾-in. wrought iron bars, and placed 1½ to 2 inches apart. These bars are not attached in any way to the bearers and are long enough to protrude a foot or more beyond the fire bed, so that they can easily be moved about for removing clinkers and readily replaced when burned out. About 16 inches above these bars a 10-in. square hole into the fire box on the front side of the furnace is provided for firing. The neck, at the other end of the furnace, is fully described as an inclined fire brick flue. As the temperature is always high in this part of the furnace, it is frequently lined with a course of best quality silica brick. For the same reason, the arch, or top, of the neck is preferably made of blocks of the same material and built independently of the rest of the furnace roof to lessen and facilitate the work of repairing. The neck terminates in a short up-take, or vertical flue, that leads to the stack, which is independently supported upon a mantle. At the base of the up-take, directly opposite the neck, is an opening or door, called the **floss hole,** which is provided primarily for the removal of the cinder that is carried, or overflows, from the puddling basin.

The Hearth, or puddling basin, is the most vital part of the furnace. Externally, the bottom of this basin consists of three iron plates, 1-in. thick, which are supported upon four heavy bearer bars laid transversely across the space between the side walls of the furnace. This construction secures all the benefits of air cooling. A low brick wall laid across the furnace, and known as the **bridge,** separates the hearth from the fire place and also serves as a backing for one end of the basin. It rises to a height of about 20 inches above the grate and is about 18 inches wide. Similarly, at the opposite end of the hearth, a somewhat lighter and lower wall known as the **breast wall** or **altar,** separates the basin from the neck. Imbedded in each of these walls next to the lining, is a hollow iron casting, called a **chill,** through which air or water may be circulated to keep these parts cool. The other two sides of the basin are supported by the walls of the furnace itself, and are similarly air cooled. One side of the furnace, usually the right side with the observer facing the fire place, is known as the back, and the other side as the front. The **back wall** is built up

solid to the roof, but the **front wall** contains the opening to the hearth, which is located directly above the basin and opposite its middle point. It is an arched opening about 20 inches square, with its top coincident with the top of the furnace and its bottom about 10 inches below the top of the bridge and 2 inches below the top of the altar. Its sides are made of specially formed silica brick, known as the **jams,** while its bottom is made of a heavy iron plate called the **fore plate.** This opening is closed by a brick-lined sliding door, which is lifted vertically by means of a lever attached to the iron frame work of the furnace. In the bottom of this door and cut on its center line, is a small inverted U-shaped opening, the **rabbling hole,** about 4 inches wide, through which tools for working the heat may be inserted without raising the door.

Accessories and Tools: After the furnace has been completed, a space about 8 feet wide along the front is leveled off, tamped well, and covered with heavy cast iron plates to form a working floor. A coal bin is built at the front end near the fire place, and a water trough, the **bosh,** for cooling the puddling tools is placed at the other end of the furnace parallel to the neck. These tools consist of 3 or 4 **paddles,** heavy iron bars about 8 feet long and sharpened on one end similar to a crow bar; 2 or 3 **rabbles,** made of iron bars similar to paddles but with about 4 inches of the working end bent at a right angle; 2 **daubbers** which are iron tools resembling a hoe but much heavier; a small short-handled scoop; and a coal shovel. Each furnace is also provided with a pair of heavy long-handled tongs, which are suspended from an overhead trolley leading from the furnace door to the squeezer. Of course, some means of bringing the pig iron to the furnace, which is usually by wheelbarrows, must be provided, as well as a scale for weighing the metal. A grinding pan or similar device for crushing and mixing the ores for patching the lining of the furnace is also desirable, but one of these mills can serve several furnaces.

Lining the Hearth: Before the newly built furnace can be put into productive operation, a smooth one-piece working bottom or basin must be built up in the hearth, for which the bottom plates and side walls already described serve merely as a foundation or backing. The details of this operation may be varied considerably with equally good results, but in general the procedure is about as follows: A very refractory fettling, composed mainly of ferric, or magnetic, oxide of iron in the form of small pieces, is spread upon the bottom plates to a depth of 2 inches and banked up slightly against the walls. This fettling may be made by calcining old furnace cinder, or a high grade ore with a low silica content, or it may be prepared from heating furnace cinder made on an oxide or magnesite bottom; magnesite, bauxite and dolomite are too refractory to be fritted in this type of furnace. The interstices are now filled by sprinkling upon this bed a quantity of clean roll scale from the finishing mills. A small fire is next built upon the grate, and the furnace is gradually heated to

the highest temperature attainable, which should be sufficient to soften the fettling so its particles will cohere. When this object has been attained, about 150 pounds of scrap iron is charged and heated to a welding heat. With paddle and rabble, the puddler then collects this iron into a ball, which, with melted oxides dripping from it, he works over the bottom until it has become one solid compact mass and presents a uniformly smooth surface. The door is now raised, and more of the coarse fettling is distributed around the edge of the slight basin to build up the walls to the top levels of the bridge and altar. Some finely divided fettling of a more readily fusible character, such as muck mill scale, is sprinkled on this material and heated till it melts, filling all the interstices of the coarser backing. Finally, just before charging the furnace for the first heat, the breast and bridge wall of the basin are covered with a thick coating of a stiff mortar, or "fix," made by grinding purple, or a mixture of red and brown, hematite ore with enough water to make it plastic.

SECTION III.

OPERATIONS TO PRODUCE PUDDLED IRON.

The Working of a Heat, or charge, takes place in more or less well defined steps, or stages, which, for convenience of ready reference, are here described as follows:

1. **Charging.** After the bottom of a new furnace has been prepared as described above, some 50 pounds or more of muck mill or squeezer scale, or old cinder, is shoveled in and allowed to melt to form a slag bath to cover the pig iron as it melts. After the first heat, this addition is never made, as enough slag from the previous heat is allowed to remain for the purpose. This slag, rich in oxides, also prevents the wearing away of the bottom by combining with the silica formed from the oxidation of the silicon during the early stages of purifying the pig iron. The actual charging is simply and quickly done. The pig iron, in pieces weighing about 50 pounds and already delivered upon the working floor, is thrown by hand through the open door upon the hearth. As the charge weighs only about 500 pounds, the puddler and his assistant can do this work in about two minutes.

2. **Melting.** As soon as the charge is in the furnace, one of the men lowers the door, stops up the puddling hole at the bottom with a little scale or coal placed with a shovel, and adjusts the shields, of which there are two, an upper and a lower. The upper is a light iron plate hung upon a trolley so as to be easily moved along the furnace front. During the working of a heat it is placed directly before the door, where it extends

for about 2 feet on both sides to protect the puddler from the heat. The lower, or slag, shield is a crescent curved plate set on the floor just below the puddling hole to shield the puddler from the heat of the slag that flows out of this hole. In the meantime, the second workman has been firing vigorously, which consists of raising the damper and closing all openings, so as to get the full draft of the stack on the fire, and of shoveling coal into the fire place, poking the fire and cleaning out the clinkers as necessary. After 10 or 15 minutes the pigs are turned over with a bar, and the door is again closed as before. In a few minutes more the iron is melting rapidly. As it melts it trickles to the bottom, where it collects in a puddle, or pool, beneath the slag. When the greater portion of the iron has been melted, the puddler inserts a paddle through the puddling hole and raises any pieces of iron covered by the slag and metal to a point where they will melt more rapidly. Thus, in from 20 to 25 minutes after charging, the metal has been completely melted and is lying quietly in a pool on the bottom.

3. **Clearing.** During the next 8 or 10 minutes, the puddler, changing his paddle for a rabble, continues to stir the metal until it has **cleared.** This point he judges from the appearance of the metal uncovered from the slag by the motion of his rabble. The change being but a slight one and occurring gradually, requires considerable experience to detect, but by close observation the iron will be seen to change from a reddish to a bluish hue. This term does not imply merely a completion of the fusion of the iron nor a "clearing" of the iron from "dirt," but a change in the character of the metal. Thus, no matter what grade of iron is used to start with, whether white, mottled or gray, a fracture test taken of the ron at this time will always show a white or "chill" surface. This result is due to the fact that all the carbon now remains combined and indicates the elimination of the silicon, the presence of which in the iron tends to prevent the carbon from remaining in combined form and to precipitate it from the solution as graphite during the cooling. This part of the process, therefore, does the work of the refinery fire so essential in dry puddling and "knobbling."

4. **Bringing on the Boil.** As soon as the metal has been properly cleared, the next step is to "raise the heat," or bring on the boil, without delay. So the damper is lowered to reduce the draft, and a little coal is put on the fire to fill the furnace with a smoky flame. Then, while one of the workmen continues to stir the bath with a rabble, the other, by means of a small scoop, introduces through the puddling hole a quantity of roll scale, sufficient, in his opinion, to accomplish the result desired. The first effect of these operations is to lower the temperature, so that the iron becomes less fluid and the slag assumes a pasty condition. This lowering of the temperature is important, for if the high temperature were maintained until the carbon began to be eliminated rapidly, there would be great danger of holding the phosphorus in the metal or of reducing

some of that already oxidized and neutralized by the slag. The metal now must be stirred constantly and vigorously, else it may solidify on the bottom or act on the lining, and in order to hasten the action, the puddler endeavors to stir the thickened slag into the metal as much as possible. After about 10 minutes of these strenuous operations the slag has become fluid again and begins to "rise on the boil."

5. **Boiling.** The oxidation of the carbon gives carbon monoxide. This gas, being formed at every point of contact between metal and slag, rises into the latter in the form of tiny bubbles. As the slag is viscous, it holds these bubbles, preventing their escape. This action causes the slag to become foam-like, so it rises in the furnace until it is flowing freely out of the puddling hole. This action becomes more and more energetic until the gas, formed more rapidly now, frequently collects in large bubbles, which, passing up through the slag, burst into bluish flames at its surface, forming the so-called **"puddlers candles."** Having maintained this maximum intensity for a few minutes, this action gradually recedes, until, after some 20 minutes of constant stirring from the start of the boil, the slag ceases to flow from the hole. The heat is now said to be dropping, and the puddler speaks of his work as "lowering the heat." It is at this point that the phenomenon most characteristic of puddling appears. As the puddler continues stirring the bath vigorously, little granules appear in the slag, like the globules seen in churning milk when the butter begins to "come." These granules are particles of metal that have become completely decarbonized. Their formation may be explained as follows: As the carbon content of the metal is reduced, its fusion temperature rises, reaching a maximum of about 1530° C. when the carbon is all oxidized. This temperature is considerably above, say 100° C. above, the temperature of the furnace. The decarbonization takes place at the surface of contact between slag and metal, and if these liquids were permitted to lie quietly, the decarbonized iron would freeze at the surface of the metal bath somewhat like ice on a pond, except that the frozen iron is not hard and brittle, but soft and pasty. The constant agitation of the bath with the rabble, combined with the ebullient action of the bath itself, breaks up this film, as fast as formed, into globules or granules, which become entangled with the slag from the same causes. As this process continues, the bath becomes stiff or pasty and very hard to work. Fortunately, it progresses rapidly, so that, in 6 to 8 minutes, the whole bath has "come to nature," as the puddlers call this result.

6. **Turning and Balling** are now the next steps. The granules of metal tend to collect in masses on the bottom. These masses must be constantly raised and exposed to the heat of the flame above, else they will stick to the cold bottom. So, substituting the bar-like "paddle" for the rabble and adjusting the draft and the fire in the furnace to give a welding heat, the puddler turns the metal until it has all been collected into what is practically one mass. Then, by punching and prying at this

mass, he manages to separate a piece, equal to about one-third of the whole, which he manipulates into a "ball" and rolls up toward the breast of the hearth. He next divides the remainder into two balls which are pushed back against the bridge wall, for, if two balls are allowed to touch each other, they become welded together again. The balling requires about 15 minutes.

7. **Drawing and Preparing the Furnace for the Next Heat:** As soon as the balling operation has been completed, the shield is pushed aside, the door is raised, and the balls are removed, one at a time, and carried to the squeezer by means of the tongs suspended from a trolley above. When the last ball has been removed, a little water is thrown on the breast and bridge walls to cool them somewhat, after which they are repaired and covered again with the ore mixture, or "fix." The bottom of the hearth is also examined and repaired, if necessary, though repairs to the bottom are seldom needed. If a bottom is properly put in at the start, and the heats properly handled, it will last for many years with a little attention from time to time. As some slag remains in the hearth from the last heat, the furnace is immediately charged again, when the operations just described are repeated in order.

Shingling or Squeezing the Ball: Before the balls of iron, which are of very irregular shape, can be rolled into bars, it is necessary to work them into a shape that can be fed to rolls, and to expel some of the slag, especially the larger portions enclosed by pockets formed within the ball. Originally, this work was done with the hammer, and the operation was

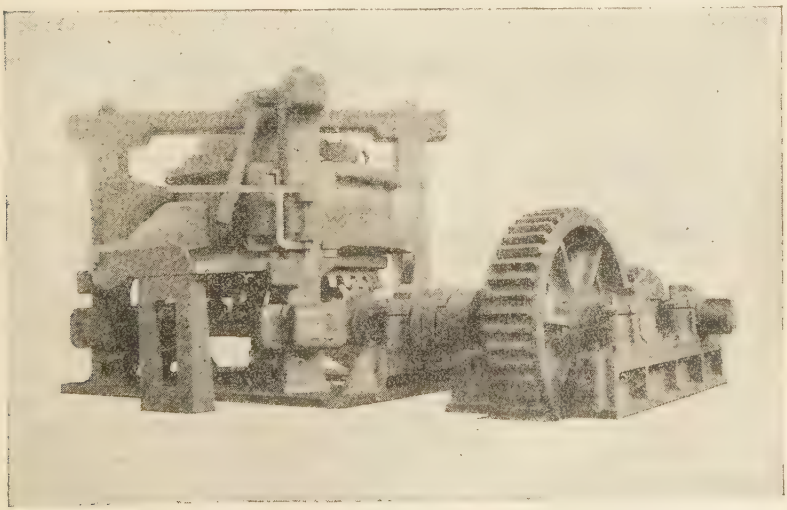


FIG. 63. The Squeezer.

known as **shingling.** In some localities it is still the practice to shingle the balls, but in this country the use of a hammer has generally been superseded by a device known as the squeezer from its action upon the ball. Several different types of squeezers have been invented, but the one now most generally used is known as the Burden Squeezer and is of the rotary type. It consists essentially of a toothed cylinder mounted upon a vertical shaft so as to revolve within a section of a somewhat larger stationary cylinder set eccentrically to the revolving cylinder and bearing teeth or cogs on its inner surface. As the larger cylinder does not describe a complete circle, but only about ¾ of a circumference, two openings are provided, a large one for inserting the ball and a much smaller one for the exit. As the irregular ball from the puddling furnace is inserted into the larger of these openings, it is gripped by the revolving cogged cylinder and carried, also revolving, around the ever diminishing space enclosed by the two circles to the smaller opening, where it drops upon a small table. This action squeezes much of the excess slag out of the ball, and works it into the form of a rough cylinder, which is grasped with tongs by a workman, and delivered to the first pass in the muck mill.

Rolling the Squeezed Ball: The muck, or puddle, mill for rolling the squeezed ball into muck bar is a 16- to 20-inch mill[1] and consists of a single stand or set of rolls, or of two stands in train, that is, end to end and coupled together. The first pass is of the open box type (see Fig. 119, page 439) with large fillets at the corners in order to take the cylinder from the squeezer, while the second pass, generally an edging pass, is of similar design, thus working the metal into the form of a round cornered square and squeezing out more of the slag at each pass. The remaining passes are all of the closed box or tongue and groove type for rolling the bloom into flats, with some open-box edging passes for use in producing the narrower widths. The size of the muck bars, of course, is regulated by the product to be made from them and the manner or system used in forming the product. For ordinary bar iron, which is the chief product, since puddled iron is no longer used for sheets or plates, the muck bar is usually about ¾ inch thick and 2½ to 8 inches wide. Bars of these sizes require from 5 to 9 passes. On account of the rapid cooling of the bar in the rolls, it is not practicable to attempt to roll sizes smaller than these, as the slag is no longer fluid enough to be worked out of the bar. As slag is being squeezed out of the bar at all passes in the mill, the muck bar has a very rough surface with some torn edges and is otherwise unfit to do service as a finished bar. Having been rolled to the size required, the muck bar is allowed to cool before being subjected to further treatment.

[1]The size of a rolling mill is determined by the distance from center to center of the pinions, but for the present it may be considered as indicating the approximate diameter of the rolls.

SECTION IV.

THE CHEMISTRY OF THE PROCESS.

Physical and Chemical Principles of Puddling: In order that the reader may the more readily understand certain phases of this subject to be discussed later, it is advisable to interrupt the sequence of the mechanical operations to discuss the Physics and Chemistry of the process, for, as indicated in the preceding description, the purification of the pig iron is brought about by chemical reactions controlled to a considerable extent by temperature regulation and mechanical manipulation. Perhaps, the most logical way to attack this problem is to ascertain the changes that take place during each successive stage of the process. To assist in this study some analyses will be found in the following two tables, showing, as far as is practicable, the chemical history of a single heat. Before beginning this discussion, however, it is well to emphasize the fact that the heat was made by puddlers of no unusual skill, and with no more than ordinary care, and was one of five heats made in 8 hours. Hence, the results are far from representing the best that can be done by the process. Besides, the pig iron is a coke iron of common grade, and as will be shown later, the grade of the pig iron has a profound bearing upon the quality and properties of the product.

Table 29. Chemical History of a Heat of Puddled Iron Illustrating Elimination of Metalloids from Pig Iron by the Puddling Process.

PRODUCT	Per Cent. Total Carbon	Per Cent. Manganese	Per Cent. Phosphorus	Per Cent. Sulphur	Per Cent. Silicon
Pig Iron Average sample composed of piece from each pig charged	3.32	.70	.764	.028	1.55
Refined Metal (After melting and clearing).	3.43	.22	.425	.033	.40
Muck Bar—Ball No. 1.....	.05	.04	.194	.026	.19
Muck Bar—Ball No. 2.....	.05	.07	.291	.025	.25
Muck Bar—Ball No. 3.....	.05	.08	.230	.025	.18
Merchant Bar—Single rolled from ball No. 3.....	.05	.06	.182	.020	.24

Table 30. Analysis of Slag—Sample of Boilings Taken Near Middle of the Boil. Same Heat As That Taken for Table 29.

		Per Cent.
Silica,	SiO_2	14.80
Ferrous Oxide,	FeO	63.85
Ferric Oxide,	Fe_2O_3	8.72
Manganous Oxide,	MnO	2.22
Phosphoric Acid,	P_2O_5	3.82
Sulphuric Acid,	SO_3	.65
Sulphur as Sulphide,		.07
Alumina,	Al_2O_3	2.62
Lime,	CaO	Trace
Magnesia,	MgO	1.30

Changes During the Melting and Clearing of the Metal: By referring to these tables, it will be observed that, by the end of the clearing stage, about three-fourths of the silicon, one-third of the manganese, and three-sevenths, or considerably less than one-half, of the phosphorus have been eliminated from the metal, while the carbon and sulphur show a slight increase. These eliminations and additions are all characteristic of the process at this stage. The slight increase in carbon and sulphur content may be attributed in part to a decrease in the weight of metal due to elimination of other metalloids and in part to absorption from the flame. If the pig iron carries a very high percentage of sulphur, a decrease will sometimes be noted at this stage. Concerning the selective elimination of the silicon, manganese, phosphorus, and carbon, the same laws hold for this process as for many other chemical processes, namely, that if a number of substances capable of reacting with each other are brought together, those reactions that liberate the most heat will occur first, and the speed of the reactions will vary with the relative masses of the reacting substances. That the elimination of these elements is brought about through a process of oxidation and neutralization is shown by an analysis of the slags formed. Analysis also shows what the neutralizing agents are, and indicates the chemical composition of the products, but the question as to what is the actual oxidizing agent is somewhat more difficult to decide. That oxides of iron and not oxygen of the air or other gases are the chief agents is evident from the fact that in dry puddling the elimination of silicon, manganese, and phosphorus was a long and difficult process, making the use of a refinery for this purpose almost a necessity, whereas with iron oxides present this work is accomplished easily and quickly. As to what oxides are involved, three theories have been advanced, namely, the magnetic oxide theory of Siemens, the ferric oxide theory of Snelus, and the ferrous oxide theory of Grüner. Of these theories, either the first or the last is the correct one, for the simple reason that, while ferric oxide is, or may be, added as fettling or

flux, it is very difficult to fuse and is rapidly reduced to the magnetic oxide by heat and reducing gases in the furnace. But while this fact leaves magnetic oxide of iron as the only source of oxygen, it does not follow that the oxidation is brought about by direct action between the metalloids and this oxide. Owing to the costs of the necessary investigations, the experimental difficulties involved, and the doubt as to the practical value of the information if obtained, the question as to just what reactions are involved in the elimination of the metalloids from the metal has never been satisfactorily answered. A careful analysis of the problem, however, indicates that FeO and not Fe_3O_4 must play the most active part in this process. In support of this theory a study of all the possibilities in connection with the elimination of one of the metalloids, such as silicon, may be found profitable.

Silicon Reactions: I. Since the temperature is very low, the final product of the oxidation and neutralization must be an easily fused iron silicate. Such easily fused compounds may be salts of either meta or orthosilicic acids.

II. A ferric silicate cannot be formed because an analysis of the cinders formed in the early stages of the process show a ferric iron content insufficient to neutralize more than about one-third of the silica to form an easily fusible silicate, whereas the ferrous iron is always sufficient to neutralize the silica, the other acids, and give some excess. Besides, if a ferric silicate is charged in a heat it is reduced to a ferrous silicate, thus acting as an oxidizing agent like ore.

III. Assuming that Fe_3O_4 acts direct and that the silicon is oxidized and neutralized in one step, all the exothermic reactions that will form easily fusible silicates are represented by the following reactions:

1. $4\,Si+3\,Fe_3O_4=5\,Fe+4\,FeOSiO_2$
1-a. $Si+Fe_3O_4 = Fe+FeO+FeOSiO_2$
1-b. $Si+2\,Fe_3O_4=5\,FeO+FeOSiO_2$
2. $6\,Si+5\,Fe_3O_4=7\,Fe+2(FeO)_4(SiO_2)_3$
2-a. $3\,Si+4\,Fe_3O_4=2\,Fe+6\,FeO+(FeO)_4(SiO_2)_3$
3. $Si+Fe_3O_4= Fe+(FeO)_2SiO_2$
3-a. $Si+2\,Fe_3O_4=4\,FeO+(FeO)_2SiO_2$

Of the various silicates formed by these reactions, the ferrous orthosilicate in 3 and 3-a corresponds most closely to the ferrous iron content of the slag. This evidence, of course, is not conclusive in itself, for another silicate may be formed with an excess of FeO, as in 1-b, or 2-a. But this evidence is strengthened by the fact that if the silica content of a relatively pure oxide slag exceeds 25 per cent., phosphorus cannot be removed without the addition of some iron oxide, indicating that there is no uncombined oxides remaining in the slag. As the percentage composition of the compound $(FeO)_2SiO_2$ is approximately 30 per cent. SiO_2 and 70 per

cent. FeO, this evidence is most convincing. But while these facts strongly indicate that the formula of the product is $(FeO)_2SiO_2$, they do not prove that either reaction 3 or 3-a actually take place. Indeed, an analysis of slags will generally show an excess of ferrous iron over the amount required to combine with all the acids and with the ferric iron to form magnetic oxide, which fact would indicate that reaction 3 does not take place, at least as long as an excess of Fe_3O_4 is present. As reaction 3-a gives too great an excess of ferrous oxide, especially in the slag formed up to the boiling stage, in which the excess of FeO is very small, only these two conclusions remain; either both reactions occur simultaneously or neither occur at all.

Table 31. Analysis of Puddle Cinders, Showing Excess Ferrous Oxide at Different Stages in Working a Heat of Puddle Iron.

1. Clearing Cinder.

SiO_2	=20.70%	=70.28%	$(FeO)_2SiO_2$	—FeO required	=49.32
Fe_2O_3	= 6.22%	= 9.02%	Fe_3O_4	—FeO "	= 2.87
P_2O_5	= 4.68%	=11.67%	$(FeO)_3P_2O_5$	—FeO "	= 7.15
FeO	=59.40%	90.97%			59.34
		.06	Excess FeO		= 0.06*
Totals	91.00	91.03			59.40

2. Starting Boil.

SiO	=15.11	=51.37%	$(FeO)_2SiO_2$	—FeO required	=36.26
Fe_2O_3	= 8.58	=12.44%	Fe_3O_4	—FeO "	= 3.86
P_2O_5	= 4.26	=10.74%	$(FeO)_3P_2O_5$	—FeO "	= 6.48
FeO	=64.74	74.55			46.60
		18.14	Excess FeO		=18.14*
Totals	92.69	92.69			64.74

3. Middle of Boil.

SiO_2	=14.80	=50.32%	$(FeO)_2SiO_2$	—FeO required	=35.52
Fe_2O_3	= 8.72	=12.54%	Fe_3O_4	—FeO "	= 3.82
P_2O_5	= 3.82	= 9.63%	$(FeO)_3P_2O_5$	—FeO "	= 5.81
FeO	=63.85	72.49			45.15
		18.70	Excess FeO		=18.70*
Totals	91.19	91.19			63.85

*If allowance be made for the acids neutralized by the manganous oxide, alumina, lime and magnesia, the excess of FeO will be from 5 to 8 per cent. greater in each case than that shown.

IV. That the silicon is oxidized and neutralized in two successive steps with the formation of the ferrous orthosilicate is the only possible supposition remaining in connection with the direct action of magnetic oxide. Since the reaction, $2\,Si+Fe_3O_4=2SiO_2+3\,Fe$, leaves only Fe_3O_4 to neutralize the silica, it is not likely to represent the first step, because Fe_3O_4 forms no corresponding salts, but, when treated with acids, both ferrous and ferric salts are formed. Only the following remains as a likely supposition, namely, that the silicon is first oxidized thus:

$$Si+2Fe_3O_4=SiO_2+6FeO$$

and the silica thus formed is immediately neutralized by the FeO, thus:

$$SiO_2+2FeO=(FeO)_2SiO_2.$$

If these two reactions be added together, the following is obtained:

$$Si+2\,Fe_3O_4=4\,FeO+(FeO)_2SiO_2$$

This reaction is identical with 3-a in the previous supposition, hence, open to the same doubts, because of the large excess of FeO it would produce.

V. The chief obstacle to the acceptance of the ferrous oxide theory is the condition that if this oxide acts as both the oxidizing and the neutralizing agent, it must be supplied through some intermediate reaction by reduction of Fe_3O_4. To prove, experimentally, that such an intermediate reaction does or does not take place is a difficult feat, but analysis of the products and raw materials, acquaintance with the chemical properties of the elements and compounds involved, combined with some knowledge of chemical laws, aid in forming some conclusions as to the changes that must take place. With such facts and knowledge, we are led to believe that molten iron in contact with molten magnetic oxide will reduce the latter forming ferrous oxide thus: $Fe+Fe_3O_4 \leftrightarrows 4\,FeO$. This reaction absorbs a little heat and occurs only at the surfaces of contact between liquid iron and liquid slag. It does not take place to completion, but only until equilibrium is established or as long as FeO is being removed from the field of action. Its extent will also depend upon the temperature. The furnace gases are also capable of reducing the magnetic oxide according to this reaction: $CO+Fe_3O_4 \leftrightarrows CO_2+3\,FeO$. This reaction, also, will fail to go to completion in either direction, for whether it is reducing or oxidizing depends upon the relative amounts of FeO and Fe_3O_4 in the slag, the proportion of CO and CO_2 in the furnace gases, and the temperature.

With FeO being constantly supplied by independent reactions, such as those above, not only would the composition of the slag at the different stages of the process be automatically regulated to correspond to the analytical results, but the oxidation and neutralization of the silicon, in either one or two steps, becomes a simple process represented by the following reactions:

$$Si+4\,FeO=(FeO)_2\,SiO_2+2\,Fe \quad \text{or}$$
$$Si+2\,FeO=SiO_2+2\,Fe$$
$$SiO_2+2\,FeO=(FeO)_2\,SiO_2$$

Furthermore, this theory provides that if the slag or metal should become impoverished of FeO in the immediate vicinity of the oxidation process, a metasilicate, $FeO\,SiO_2$, may be formed, which, upon rising into the slag, can combine with more ferrous oxide to form the orthosilicate $(FeO)_2SiO_2$, thus:

$$FeO{\cdot}SiO_2+FeO=(FeO)_2\,SiO_2$$

Elimination of Manganese and Sulphur: Assuming that FeO is the more active oxidizing agent, the elimination of the manganese may be represented by the following simple reaction: $Mn+FeO=MnO+Fe$. The manganous oxide, being insoluble in the metal, rises into the slag, where it probably helps to neutralize the silica, thus: $2\,MnO+SiO_2=(MnO)_2\,SiO_2$. Observations seem to indicate that the elimination of the manganese occurs simultaneously with the oxidation and neutralization of the silicon, in which case the following reaction may be correct: $Si+Mn+4\,FeO=MnO{\cdot}FeO{\cdot}SiO_2+3\,Fe$. A little manganese may also reach the slag in the form of manganese sulphide, which then combines with oxygen, forming manganous and sulphurous oxides. The latter would then escape as a gas. This is probably the chief manner in which sulphur is eliminated, for it is a matter of common experience that unless the manganese content of the pig iron is high, very little sulphur is eliminated. When the sulphur content of the pig iron is very high, say above .1 per cent., it may be reduced considerably in amount, but its elimination to a point under .060 per cent. is very uncertain. Hence, the only sure way to control the sulphur in the puddled iron is by the use of low sulphur pig iron.

Elimination of Phosphorus: The oxidation of phosphorus, which is probably combined with the iron as the phosphide, Fe_3P, results in the formation of phosphoric anhydride, P_2O_5, which, being an acid, must be immediately neutralized by some base in order to be held in the slag. The only base available is ferrous oxide, hence the final product is ferrous phosphate, $(FeO)_3P_2O_5$. The oxidation and neutralization is conveniently represented by these two reactions: $5\,FeO+2\,Fe_3P=P_2O_5+11\,Fe$ and $P_2O_5+3\,FeO=(FeO)_3P_2O_5$. As the oxidation and neutralization must be almost simultaneous, these changes may be represented by a single reaction, thus: $2\,Fe_3P+8\,FeO=(FeO)_3P_2O_5+11\,Fe$.

As indicated by the preceding table, the phosphorus elimination occurs during the clearing stage and the first part of the boil, hence is affected by both the silicon and the carbon. Since the oxidation of both silicon and manganese gives off more heat per atom oxidized than phosphorus, and are usually present in larger amounts, the phosphorus has little chance of being oxidized until the others have been largely eliminated. Besides, silica is a stronger acid than phosphoric anhydride and will displace the latter if no free ferrous oxide is available for its neutralization. In the method of procedure outlined in describing this process, this free ferrous oxide must be supplied from the fettling, or "fix," so that there is little

excess of ferrous oxide during the melting and clearing stages. Therefore, it would appear advisable to add all the scale required before charging the metal, as some puddlers prefer, but as this procedure increases the amount of slag, which delays the melting, and tends to bring on the boil too rapidly, making it necessary to cool the bath with water, most puddlers adhere to the method as given.

Elimination of Carbon: Simple observation is sufficient proof that the carbon is eliminated as carbon monoxide, and as the only oxidizing agents present are ferrous and ferroso ferric oxides, the reactions possible are:

1. $FeO+Fe_3C=CO+4\ Fe$ — 45000 cals.
Heats of formation 65700 8460 29160
2. $Fe_3O_4+Fe_3C=CO+3\ FeO+3Fe$ — 53000 cals.
Heats of formation 270800 8460 29160 65700
3. $Fe_3O_4+4\ Fe_3C=4\ CO+15\ Fe$ —188000 cals.
Heats of formation 270800 8460 29160

All these reactions are endothermic, hence none are likely to become very active as long as the temperature is low; and since No. 1 absorbs less heat than either of the two others, we would expect it to take place in preference to the others in the presence of both oxides. This reaction will go to completion, because one of the products of the reaction, CO, is a gas which escapes from the field of action as rapidly as formed, so carbon is eliminated till only a trace remains. Rising into the slag in the form of tiny bubbles, the carbon monoxide is held there, causing the slag to rise like foam. Since this gas is reducing, it is capable of producing a change in the slag composition so long as the temperature remains below the decomposition point of CO_2 (1250-1300° C.), according to the following reversible reaction: $Fe_3O_4+CO \leftrightarrows CO_2+3FeO$. This reaction does not go to completion in either direction, but, after the scale has been added, will progress rapidly to the right until equilibrium is established, which, since the pressure is constant, will depend upon the temperature. This action accounts for the large and almost constant excess of ferrous oxide found in the slag up to the middle of the boil.

Relation of Carbon to Phosphorus Elimination: The matter of greatest practical importance is the influence the oxidation of the carbon has upon the elimination of phosphorus. As the temperature is raised after the clearing stage, the carbon reaction becomes more and more vigorous, and when this action has become violent enough to produce a "boil," no more phosphorus can be removed for two reasons: First, the active mass of the carbon throughout the boil is so much greater than that of the phosphorus that it robs the entire field of action of all available ferrous oxide. Second, as the carbon is removed the fusion point of the metal rises accordingly until it approaches the maximum temperature that can be attained by the furnace. Then, as more carbon is

removed, but before it has reached a concentration that will permit the ferrous oxide to act upon the phosphorus, the metal begins to crystallize, especially near the surface of the metallic bath. These crystals carry some carbon and some phosphorus, but are purer than the mother metal, so this process tends to hold the carbon and phosphorus in the mother metal at a constant ratio, while only the carbon is being eliminated. Finally, before the carbon has been eliminated to a point that will permit the oxidation of the phosphorus, the mother metal that remains is pure enough to crystallize. After solidification has taken place, phosphorus cannot be eliminated at all, while the oxidation of the carbon may continue, but, of course, much more slowly. The reason carbon can be burned out of the solid metal is that it forms a solid solution at these temperatures, hence is easily diffused to the surface, where its oxidation removes it from the field of action. Phosphorus does not diffuse so readily, and its oxidation, the product of which is a solid or liquid, does not remove it from the field of action.

Practical Control of the Phosphorus: From the remarks above, it will be apparent that the elimination of the phosphorus from a given pig iron will depend upon the skill of the puddler, the purity and quantity of the fettling and flux used, and the working efficiency of the furnace, by which is meant both the heating capacity of the furnace and its facilities for permitting control of the temperature. Besides, the percentage of phosphorus remaining in the puddled iron is affected by the quantity present in the pig iron. Thus, because of the influence of concentration upon the speed of the reactions, very little, if any, phosphorus can be removed from a low phosphorus pig iron, but as the phosphorus content of the pig iron is increased above .040 or .050 per cent., it becomes easier and easier to oxidize the element, and correspondingly larger proportions can be eliminated, leaving, of course, correspondingly greater percentages in the puddled iron. Therefore, by carefully standardizing the method of working the heats, it is possible to control the phosphorus content of puddled iron through selection of the pig iron. This matter is of importance to the manufacturer and users of wrought iron, because it offers the only practical means, aside from cold working, by which the strength of puddled iron can be controlled. The effect of phosphorus upon the tensile properties of wrought iron is shown by the table on following page.

There is a limit, however, to the increase of strength to be gained through increasing the phosphorus content of wrought iron, lest the iron become cold short. To test for this property a short piece of the bar is nicked on one side, then bent until it breaks. If the iron has been properly made and the phosphorus content is normal, say under .120 per cent., the fracture will show a fibrous structure, but as the phosphorus content is increased above this percentage crystalline spots appear until, with .200 per cent. phosphorus, the fracture shows, in the case of large

Table 32. Showing Effect of Phosphorus on Tensile Properties of Wrought Iron.[1]

KIND OF IRON	CHEMICAL ANALYSIS PER CENT. OF					PHYSICAL PROPERTIES [2]				REMARKS
	C.	Mn.	S.	P.	Si.	Tensile Strength lbs. per sq. in.	Elastic Limit lbs. per sq. in.	Elongation in 8 in. Per Cent.	Reduction of Area Per Cent.	
Swedish Iron	.02	.12	.005	.017	.051	41280	30310	33.5	77.6	½-in. round. Manufacture unknown.
Hammered Iron from Knobbled Muck Bar	.02	.08	.017	.061	.02	46600	32190	36.7	59.4	$\frac{15}{16}$-in. round.
Single Rolled Bar Iron, High Phos	.05	.15	.021	.297	.33	54870	38750	23.4	33.0	Average of 3 pieces, 1-in. round.
Single Rolled Bar Iron, Normal Phos	.05	.05	.025	.150	.20	49000	33200	27.5	42.0	1-in. round.
Box Piled Double Refined Iron, High Phos.	.02	.10	.027	.178	.17	52920	37390	25.8	37.0	1⅛-in. round.
Box Piled Double Refined Iron, Normal Phos	.03	.06	.013	.125	.16	49150	34100	30.2	48.3	1-in. round.
Double Refined Hammered Iron	.03	.04	.018	.067	.11	45700	30960	33.1	54.3	Average of 5 pieces, $\frac{13}{16}$-in. round. Made from charcoal pig iron.
Hammered Billet Iron	.02	.07	.015	.113	.12	48230	32200	33.7	51.3	Made from charcoal pig iron, 1-in. round.
Hammered Billet Iron	.02	.08	.015	.115	.12	48960	32980	32.7	49.5	Made from charcoal pig iron.
Hammered Billet Iron	.02	.07	.017	.100	.13	48850	32750	31.5	49.1	Made from charcoal pig iron.
Hammered Billet Iron	.02	.08	.017	.165	.12	51240	35350	31.6	48.3	Average of 5 tests, 1-in. round.
Hammered Billet Iron	.02	.05	.016	.188	.15	51320	36425	29.5	48.7	1-in. round.
Hammered Billet Iron	.02	.05	.016	.202	.18	52420	37070	30.2	47.8	1-in. round.

[1] Data supplied by C. W. Bacher, Mgr. Brown & Co., Inc., Pittsburgh, Penna.

[2] For an explanation of the meaning of the terms used in these columns, see Chapter 1, Part II, page 410.

bars, scarcely any fibrous structure, that is, it is practically 100 per cent. crystalline. In the case of small bars, say under one inch square or round, less crystallization will appear in the fracture, as the tendency to show the crystalline structure is influenced by the size and form of the section. The presence of crystalline spots, however, cannot be taken as a positive and unfailing indication of high phosphorus, as the presence of steel, the smallness of the slag threads, and the rapidity of the application of the breaking load are also factors conducive to the formation of crystalline spots in the fracture. The same structure can also be noticed in making pulling tests of such high phosphorus iron. This crystalline structure is indicative of cold shortness, which renders the iron unsafe for many purposes. Thus, strength alone is no criterion as to the quality of the iron.

Effect of Other Elements on Strength: Of the other elements present, carbon and manganese are also capable of increasing the tensile strength of the iron, but these elements cannot be controlled. Silicon, which can be controlled to a slight extent, has little effect upon the tensile properties of the iron, but does affect its welding properties, a high silicon content making the iron more difficult to weld.

Pig Iron and Flux for Puddling: From the preceding discussion it will be surmised that the quantity and composition of the slag are of considerable importance in the process. A large amount of slag tends to prolong the operation by shielding the metal from the heat, while a small amount gives a high concentration of impurities that may retard or even prevent the maximum purification of the metal. The slag must be easily fused, for not only does a stiff viscous slag tend to retard the purification of the pig iron, but it is injurious to the iron. In order that the slag may be expelled properly in the squeezing and rolling operations, its fusion point must be well below the maximum welding temperature of the iron, which is somewhat below the melting temperature of pure iron, or 1530° C. If the fusion point of the slag should approach the welding heat, it would prevent the welding of the particles of iron, thus causing what is known as "slag short" iron. Therefore, lime cannot be used as a flux, and the cinder from the furnace, though it contains the equivalent of 50 per cent. metallic iron, cannot be used again except in very limited amounts, and is generally sold for blast furnace consumption. The ore used for fettling is selected mainly for its refractoriness, but it automatically supplies a good portion of flux. On both accounts it should have a low silica and phosphorus content. While ore may be used for flux, roll scale is a waste product from the mills and is very pure, except that produced by the squeezer and muck mill. Scale from the latter should not be used for the best grades of iron. The composition of the slag is, of course, influenced by the amount of impurities in the pig iron. An iron with a high silicon, manganese and phosphorus content will make more slag than one low in these elements. Besides, if the silicon is high, say, above 1.50 per cent., it will tend to delay the elimination of phos-

phorus, while if it is much below 1.00 per cent., the iron phosphate will be so highly concentrated in the slag that there will also be danger of ending with high phosphorus in the puddled iron. With regard to the maximum phosphorus content of the pig iron, the limit is about 1.00 per cent., as such a pig iron would, under normal conditions, probably give from .170 to .200 per cent. phosphorus in the wrought iron. Of course, the specifications to which the iron is being made will determine the phosphorus content of the pig iron below this limit. As sulphur makes wrought iron hot short, as in steel, and since its elimination is variable and uncertain, the pig iron should be low in sulphur, or at least no higher than is desired in the wrought iron. One other fact should be noted, namely, that wrought iron made from charcoal pig iron is more uniform than wrought iron made from coke pig, and, though the two irons may be of the same composition chemically, the charcoal iron will, on the whole, give better results in the physical tests than the iron made from coke pig.

SECTION V.

REFINING THE MUCK BAR, AND PROPERTIES OF WROUGHT IRON.

The Importance of Mechanical Treatment in the Manufacture of Wrought Iron cannot be over-emphasized. Muck bar is an exceedingly variable product. The truth of this statement must now be apparent, but to give it additional emphasis and sum up what has already been said, we would add that this variation is due to—

1. Differences in manipulation by different operators and furnaces.

2. Irregularities in the pig iron.

3. The small quantity produced with each heat.

4. The fact that the metal solidifies before purification of the whole bath is complete.

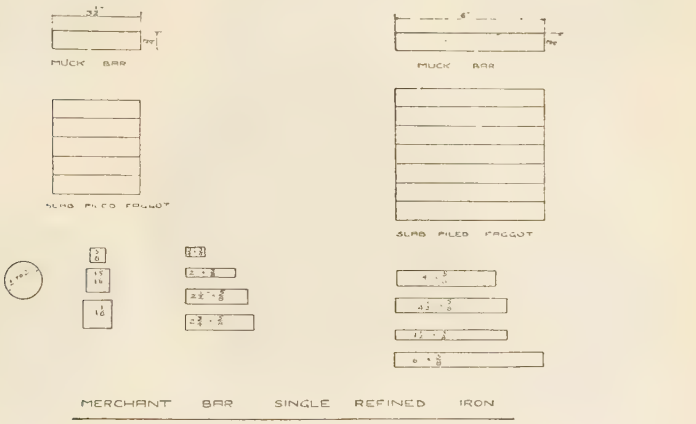
It is evident that these contributing causes of variation cannot be corrected without remelting and casting, and if the metal is to retain the

characteristics of wrought iron, it cannot be remelted. Therefore, this variation in the muck bar must be overcome through mechanical treatment that will bring about a thorough mixing of the bars.

Working the Muck Bar: Obviously, the surest way to obtain a thorough mixing of the iron, is to shear the muck bars into small pieces,—the smaller the better. These small pieces from the different muck bars are allowed to collect in a pile, or piles, from which portions weighing 180 to 600 pounds are removed with a scoop or fork and charged into a reheating furnace, called a balling furnace, where they are heated "white hot," or to a self-welding temperature. With a paddle, these pieces are now collected into a ball, similar to a puddle ball, which is squeezed or shingled, then rolled or hammered into a bloom, which is then reheated and worked into the form desired. This process, known as busheling, is carried on with high labor cost, hence is used for working up muck bar only when iron of the highest quality is desired. The process is also used in working up small scrap. In this case there is no necessity for shearing, and the cost of the scrap is usually considerably less than the cost of muck bar, but unless the scrap is very carefully selected it is liable to contain much steel, in which case the iron produced is of inferior grade. By far the more common practice, therefore, is to shear the muck bar into lengths of from 2 to 3 feet, then arrange these pieces in piles of from 5 to 7 each and bind the pieces together with wire or bands. The piles are carefully charged into a furnace and heated white hot. The high temperature causes the different bars to weld together, so that they may then be removed and rolled into bars. The first 2 or 3 passes squeeze out and more and more of the liquid slag, but in the last passes the bar has cooled to a point where the slag is merely plastic and will not flow. Thus, a fairly smooth and uniform bar is produced, which is sold as merchant bar, single rolled iron, single refined iron, or No. 2 iron. The bar, however, is still lacking in uniformity, and its slag particles, while very much elongated, are of comparatively large cross section. Furthermore, since it is built up of flat bars, it will not offer the same resistance to bending in all directions.

Double Refining: To remedy these defects the merchant bar is likewise cut up into short lengths, faggoted, reheated, and rerolled to produce the products known as double rolled iron, double refined iron, best bar, or No. 3 bar. The manner of faggoting, or piling, these bars may be varied in numerous ways, and depends only in part upon the use to which the iron is to be applied. Therefore, each manufacturer will generally have his own methods of faggoting, which imparts to his iron an individuality detected by etching. Some of the more common methods of faggoting are illustrated by the accompanying sketches (Fig. 64). When these faggots are heated and rolled into bars, more slag is expelled, the bar is made more uniform in composition, and the fibers are much elongated and reduced in size. As a result, the bars will show a decided improvement

in physical properties, including both strength and ductility. There is a limit, in addition to the factor of cost, however, to the number of times the iron can be worked to its advantage, for after 5 or 6 workings its



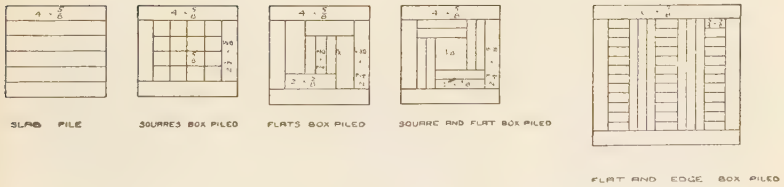


FIG. 64. Diagrams Illustrating some of the Different Methods of Piling to Produce Merchant Bar from Muck Bar and Double Refined Iron from Merchant Bar.

physical properties will begin to be lowered, and the bars will be less strong and less ductile. The cause, or causes, of this change is not known; probably, it is due to the elimination of much of the slag and of the fibrous

structure. With much working the metal fibers and slag filaments are elongated and made so fine as to become practically broken up, and the iron loses the characteristics of wrought iron, becoming more like a very dirty ingot iron or steel.

FIG. 65. Macroscopic Structure of Double Refined Wrought Iron, Showing the structure obtained by piling according to last method shown in Fig. 64. Cross Section of 1¾-inch round, Etched with tincture of iodine, Natural size.

Losses in Making and Working Puddle Iron: From a study of the probable reactions that occur in puddling, a gain in weight of the puddled iron over the pig iron used would be expected, as iron is formed by reduction from the slag in the elimination of practically all the impurities. And, by careful manipulation, furnaces have been operated to show a slight gain or a very slight loss. Nevertheless, in ordinary working, there is a loss of from 3 to 5 per cent., which is sometimes a little more, at other times a little less, than the total of the impurities present. If the heat is properly handled, the loss is largely due to oxidation of iron after crystallization has begun in the after part of the boil and during the balling stage. If the heat is not skillfully handled, a variable part of the loss may be due to the escape of the metallic granules with the "boilings" before the "heat is lowered." In reheating and rolling the muck bar, there is a variable loss, depending upon the number of times the iron is worked, the manner of the working, and many other factors incidental to the operations of heating and rolling, of from 10 to 20 per cent. for each time the iron is worked. In general, these losses are due to oxidation of the metal in heating and rolling, expulsion of the slag, and cropping. Oxidation of the metal in the reheating furnaces depends directly upon the nature of the furnace atmosphere, whether oxidizing or reducing, the time the metal remains in the furnace, and the temperature to which it is heated during that time. As nearly all the reheating

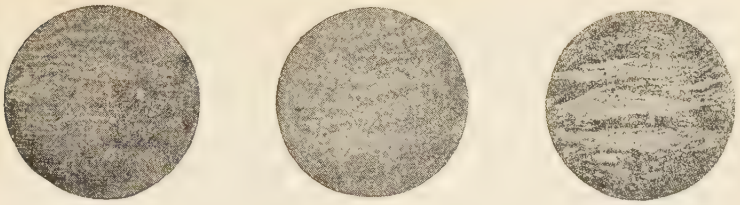


Fig. 66. Single Rolled, slab piled.

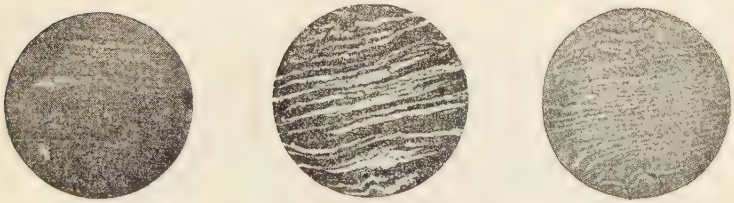


Fig. 67. Double Rolled, slab piled.

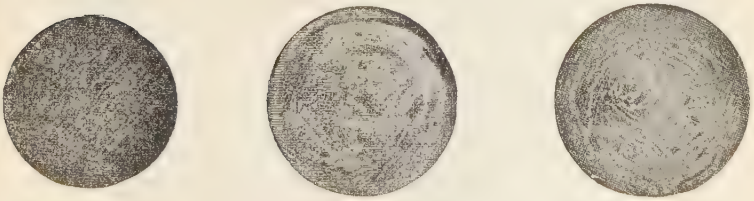


Fig. 68. Double Rolled, box piled.

Cross Sections of Wrought Iron Bars, polished, and etched with tincture of iodine. Illustrating some of the structures produced by different methods of piling. One-inch rounds, natural size.

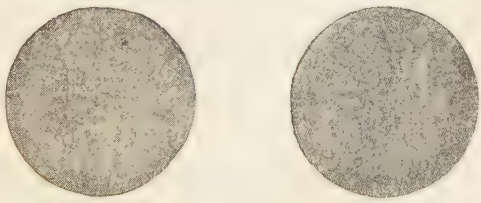


Fig. 69. Busheled, or Hammered Bloom, Iron.

furnaces in use in puddle mills are of the reverberatory type, the oxidation depends on how the furnace is operated and the way the faggots are handled. Slag expulsion is the smallest item of loss, except in the case of muck bar, and depends mainly upon the number of times the iron is worked, but is also affected by the temperature at which the iron is worked, and the nature of the incorporated slag itself. The loss is a little greater on iron with a high phosphorus content than on iron low in phosphorus. The loss due to crop ends depends largely upon the product being made. Short mill lengths produce more crop ends per ton than long ones of the same section.

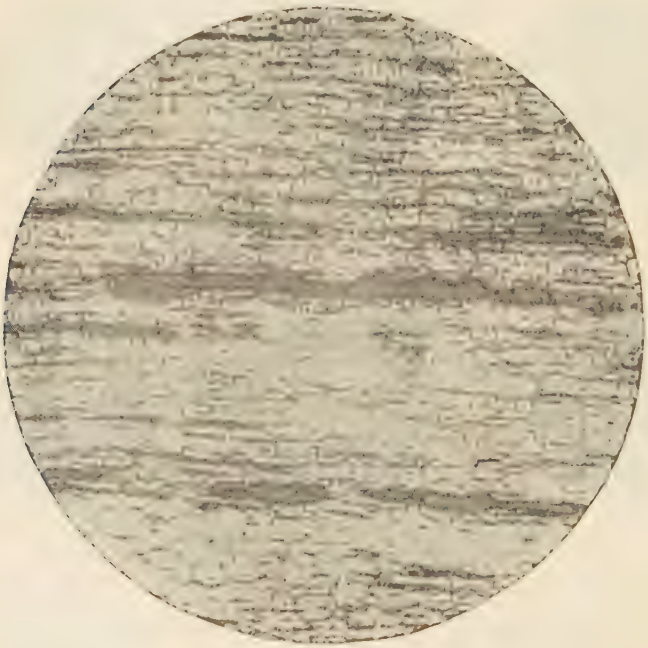


FIG. 70. Photomicrograph of Longitudinal Section of Double Refined Wrought Iron Bar, Magnified 100 Diameters. Etched with nitric acid. The grayish stringer-like bodies are slag particles. The white irregular bodies bounded by the faint dark lines are crystals of almost pure iron.

Properties and Uses of Wrought Iron: From what has been said, it will be seen that wrought iron may vary, or be made to vary, in both strength and ductility, but any increase of the former is accompanied

by a decrease of the latter property. Also, since the carbon content is uniformly low, there is a limit to which the strength may be increased with safety. This limit depends considerably on the area of the bars: for one-inch rounds, 52,000 pounds, and for two and one-half-inch rounds, 50,000 pounds is high. Strength is no indication of the quality of the iron; the best standard grades made give a tensile strength of from 46,000 to 49,000 pounds per square inch. The carbon and the manganese content of bonifide wrought iron seldom exceed .08 per cent. and .10 per cent., respectively. Hence, high tensile strength, with a carbon or a manganese content higher than these figures, indicates the iron may contain steel scrap, which may be added in either piling or busheling methods of working. Since the introduction of the pneumatic and open hearth processes, wrought iron has largely been replaced by the different varieties of steel, which is stronger, more uniform, more ductile, and cheaper in price. There are some things, however, for which wrought iron, on account of its softness, its fibrous structure, its welding properties, and its resistance to vibratory and fatigue stresses, is well suited and for which it is still used. Among these may be mentioned engine bolts, stay bolts, heavy chains, blacksmith iron, draw bars and certain other parts of locomotives, and other machines. On account of its fibrous structure, wrought iron is more easily threaded and machined than soft steel, hence was for years preferred for threaded articles that required a soft ductile iron, such as bolts, nuts, and pipe. The difficulty formerly encountered in threading or machining soft steel was that the cuttings curl like shavings and choke up the dies. By changing the design of the dies slightly, this difficulty was overcome, so steel has come to replace wrought iron in this field because of its greater cheapness. Up until 1910 it was thought by many that wrought iron, because of its low manganese content, or greater purity, offered more resistance to corrosion than steel and was preferred in sheets, wire, and pipe or tubes on this account. Many instances, however, may be cited to show that, provided the wrought iron contains no inhibitor to corrosion, such as copper, it will rust as rapidly as steel under the same conditions. It is probable that much of the wrought iron made in former times contained small amounts of copper, and the high resistance to corrosion sometimes exhibited by the metal was due to the presence of this element, which has a similar effect when added to steel. In this connection, it should be observed that quenching in water affects the tensile properties of the iron to a noticeable extent, as is shown by the following table. It may also be stated that repeated quenchings may injure wrought iron articles, as such treatment is liable to rupture the welded structures.

Table 33. Pulling Tests Made on 1-Inch Rounds to Show Effect of Quenching Wrought Iron.[1]

KIND OF IRON	TREATMENT	Ultimate Strength lbs. per sq. in.	Elastic Limit lbs. per sq. in.	Elongation in 8 in. per cent.	Reduction of Area per cent.
Single Rolled. Slab Piled.	Before Quenching	47270	31540	27.0	43.9
	After Quenching	52950	38200	22.3	41.5
Double Rolled. Slab Piled.	Before Quenching	48220	33380	31.7	52.0
	After Quenching	53380	37960	28.4	49.4
Double Rolled. Box Piled.	Before Quenching	48750	34920	29.8	45.6
	After Quenching	56470	40320	27.9	45.5
Hammered Bloom, from Sheared Muck Bar.	Before Quenching	48850	34250	33.7	54.6
	After Quenching	54230	38720	27.5	52.3

[1]From data supplied by C. W. Backer, Mgr. Brown and Co., Inc., Pittsburgh, Penna.

Testing Wrought Iron: In the absence of a satisfactory method for testing the resistance of iron to vibratory stresses, the only reliable quantitative test applied to wrought iron is the pulling test. Etching will show the presence of steel and the structure of the bar, while bending tests are merely indicative of the ductility of the metal. Since the results obtained in pulling tests may be affected by many things incidental to the operation, the conditions and the material, a thorough knowledge of all the conditions and their effect upon the results are required both in testing and in writing specifications for wrought iron. Assuming that the testing machine is correct and indicates accurately the actual tension on the test piece, the most important factor in its operation is the speed at which the piece is elongated, especially up to the elastic limit. The standard speed is ¾ inch per minute. This speed may be increased to 1 or 1½ inches without making any appreciable differences in the physical properties, but as the speed is increased above this rate, first the elastic limit, then to a much less extent the tensile or maximum strength will be observed to increase, while the elongation and reduction of area will also increase slightly. The temperature of the test piece at the time of pulling is also important, as the iron is capable of retaining its physical properties unchanged only within a certain range of temperature. Thus, as the temperature falls below 10° C. (50° F.), a slight gradual increase in the tensile strength will take place, while the ductility will decrease, until, eventually, at about —25° C. (—13° F.), the metal becomes somewhat brittle.

Relation of Test Piece to Pulling Test: The size and form of the test piece, also the manner in which it is prepared, are important factors

in testing iron. A test piece with the "skin" on, that is, with the surface produced by rolling or forging, will generally give higher tensile properties than a similar piece that has been machined all over. On account of its fibrous structure, wrought iron will also give lower tensile properties pulled at right angles to the direction of rolling, or greatest elongation in forging, than when pulled in the same direction. This difference will amount to from 4000 to 8000 pounds in the tensile strength, from 5 to 10 per cent. in the elongation, and from 8 to 20 per cent. in the reduction of area, depending on whether the material has been box piled or busheled, rolled or forged. But the factors capable of producing the most surprising effects upon the tensile properties, are the size and shape of the test pieces. Since the piece always stretches more at the point of fracture than any where else, it is important that the original length of bar on which the elongation is calculated should be stated, also this length should be about equally divided by the break. The standard length of measurement is 8 inches. The size and shape of the section, while affecting all the tensile properties, have the most marked effect upon the ductility, particularly the reduction of area. The sizes and form most favorable to the iron is a ¾- to 1½-inch round. This range of sizes offers opportunity for working the metal sufficiently to develop the fiber and refine the grain and gives a volume of metal that permits the maximum reduction, and the round has no sharp corners or edges to give way and start a fracture before the maximum load has been applied. With an increase in the size of the round all the tensile properties will decrease gradually to a minimum. After rounds, squares give the best results, while flat bars, angles and other shapes, and thin plates give poorer results in the order named. Thus, with a good grade of double refined iron, having a tensile strength of about 48000 pounds, the reduction of area may vary from about 15 per cent. in thin sections or plates to as much as 55 per cent. in a 1-inch round.

SECTION VI.

ATTEMPTS TO IMPROVE THE OPERATION OF PUDDLING.

Fuel and Waste Heat Utilization in Puddling: Following the introduction of the Bessemer and open hearth processes for manufacturing steel, many attempts were made to reduce the cost of wrought iron to a point where it could compete with soft steel. That this aim was pursued with vigor is shown from the fact that the patents connected with the process are numbered by hundreds both in this country and in England. At first these attempts aimed mainly at improvements in furnace size and design. The reverberatory furnace is very wasteful of heat. From 2000 to 2400 pounds of coal are required to produce one ton of muck bar with the simple furnace described herein. In order to reduce the waste of heat by radiation, two furnaces were built back to back. Then the dividing wall was omitted, forming the double furnace, and later the hearth was enlarged and two doors were placed on each side, forming

the double-double furnace, which permitted four puddlers to work at the same time. Even with these furnaces more than 90 per cent. of the heat from the fuel escaped up the stack, and attempts were made to recover this heat by using the waste gases to preheat the air for combustion, which could only be done to advantage with gaseous fuels. Then, waste heat boilers were installed and proved very satisfactory. These are generally vertical boilers, and form a part of the stack. In this way more than twice as much steam can be generated as is required by the rolling mills, hammers and other machinery needed to work up the product. So, unless the excess can be disposed of as electrical power, the heat waste with the boiler installation is considerable. Many other attempts to increase the heat efficiency of the furnace through changes in design have been less successful.

Mechanical Puddling: As the large amount of labor, both skilled and common, connected with the process forms one of the chief items of expense, and as the labor of puddling is very arduous, many mechanical devices to do the work of the puddler, or a large part of it, have been invented. At first these mechanical puddlers took the form of stirring or rabbling appliances that could be attached to the top of the ordinary furnace. Because of the great variety of motions necessary in the different operations of charging, raising and stirring the heat, balling the iron, and drawing the balls, none of these were successful. The more successful attempts at mechanical puddling have involved a complete change in the design of the furnace, and some changes also in the process. These attempts have been so numerous it would be unprofitable to describe all the appliances here. The furnaces themselves may be classified as follows:

1. The rectangular furnace that oscillates about a horizontal axis of rotation.
2. The circular flat-bottom furnace that revolves about an axis slightly inclined to the vertical.
3. The circular furnace with flat or trough-like bottom, that oscillates about a horizontal axis of rotation.
4. The cylindrical furnace that rotates about a horizontal axis coincident with the center.
5. The cylindrical furnace that oscillates about a horizontal axis coincident with the center, or both oscillates and rotates about such an axis.

Furnaces built on any of these plans have been made to puddle iron successfully, but those of the fourth and fifth types have been most successful, partly on account of the facilities they afford for controlling the agitation of the metal and partly because of the simplicity of their construction. The Danks furnace[1], somewhat widely used in this country from 1868 to 1885, was of the 4th type, while the Roe furnace[2], built

[1]See "The Danks Puddling Furnace", by John I. Williams; Proceedings Engineers Society of Western Penna., Vol. I, page 137, Sept. 14, 1880.; also, see Journal British Iron and Steel Institute, 1871, Vol. II, page 258.

[2]See, Journal British Iron & Steel Institute, 1906, Vol. III, Page 264.

and successfully operated by James P. Roe of Pottstown, Pa., in 1905, was of the 3d type. The most recent invention of a mechanical puddler, perhaps, is that of H. D. Hibbard[1]. His furnace, first operated on a commercial basis in 1921, is of the fifth type and somewhat similar in construction to the older Danks furnace. This furnace consists of an outer steel shell about 6 feet in diameter and 5½ feet in length and an inner layer of magnesite brick covered with a layer of iron sintered into place. It is supported upon two hollow trunnions, one at each end, about 18 inches in diameter. One of these trunnions provides the opening through which the furnace may be charged and the products of combustion may escape, while the other affords a means of introducing the fuel and air for combustion. The lower half of the cylinder, or what constitutes the working bottom of the furnace, is divided longitudinally by a Λ-shaped bridge wall. The door for discharging the metal is in the upper half over this wall. The pig iron is first melted in a cupola, from which it may flow through a trough, or runner, into the puddler. The maximum capacity of the furnace is about 1500 pounds of pig iron. As soon as the molten iron has been charged, sufficient roll scale is added to oxidize the impurities, the heating valves are opened and the furnace is slowly oscillated, by means of an electric motor and gear arrangement, so as to cause all the metal to flow back and forth over the bridge in the form of a thin sheet-like stream. This oscillating motion is continued until the metal has come to nature, when the furnace is rotated until the balling stage is completed. The door is then opened and the furnace is rotated slowly until the door is inverted, i. e. at its lowest level, when the ball, weighing from 1250 to 1400 pounds, drops out upon a steel belt conveyor which carries it to the squeezer. This squeezer is similar in construction to the ordinary type except that the axis of rotation of its smaller cylinder is horizontal instead of vertical. The squeezer delivers the bloom upon a second conveyor, which carries it to the muck mill. All hand work is eliminated, the time of running per heat is only a little more than 45 minutes, and the product is said to compare favorably with hand puddled iron.

Duplex Processes: Other attempts to produce wrought iron, having the properties of puddled iron, by a radically different process have been made from time to time since 1890, chief of which are what may be termed the duplex processes. These consist in first eliminating the silicon, manganese, and part of the carbon in a Bessemer converter, or acid open hearth, or the silicon manganese, phosphorus and part of the carbon in a basic open hearth, and then teeming this purified metal into molten mill scale in a suitable vessel. No data indicative of the quality or nature of the iron produced by these processes are available.

[1]See, The Iron Age, Vol. CX, No. 3, July 20, 1922.

CHAPTER VIII.

EARLY METHODS FOR MAKING STEEL.

SECTION I.

CEMENTATION PROCESS.

Wrought Iron and Steel: As is evident from the properties of wrought iron, pure iron, or the commercial forms representative of pure iron, is too soft and ductile to be used for many of the purposes for which it is most desirable to use it, such as tools, for example. To adapt it to these uses, it is necessary to harden and strengthen it. In general, this hardening may be accomplished in three ways, namely, by cold working; by heating to a high temperature, say a white heat, and cooling with great rapidity; or by introducing certain other elements which are capable of forming an alloy with iron. It is obvious that the effects produced by the application of either of the first two methods are confined largely to the surface. To harden any considerable body of the metal uniformly throughout, therefore, it is necessary to employ the third method. The element which is most generally added to control the properties of the metal, and which was probably also the one first knowingly used for this purpose, is carbon. The addition of carbon not only hardens the metal but imparts to it other distinctive properties, as well. Hence, the alloys of iron and carbon were early distinguished from wrought iron by a different name, which has been translated into our modern English as the word steel. As will be shown later, this term is generic rather than specific, so there are a great many varieties of steel. For the present, however, we will consider only the simplest variety, which may be defined as a malleable alloy of iron and carbon.

Ancient Methods of Steel Making: Prior to 1856 only two methods of making steel, the cementation and crucible processes, had been developed. Both of these processes were certainly known to and practiced by the ancients. The Wootz steel of India, the famous blades of Damascus, Syria, and the equally famous steels of Toledo, Spain, were all made by the crucible process, or a combination of the cementation and crucible processes, though the apparatus used would, doubtless, appear very crude to the modern metallurgist. During the middle ages both of these methods appear to have been lost to civilization. The cementation process was revived in Belgium about the year 1600, while the crucible process

was rediscovered in England by Benjamin Huntsman in 1742. Both processes were practiced in secret for some time after their revival, hence little is known of their early history. The following brief descriptions will, therefore, be confined to the more modern practices.

The Cementation Process was highly developed and flourished in England during the 18th and 19th centuries, and, though fast giving way to other methods, is still practiced to a limited extent. The process depends upon the fact that when a low carbon ferrous product, such as wrought iron, is heated to a red heat in contact with charcoal or other carbonaceous material, the metal absorbs carbon, which, up to the saturation point of slightly less than 2.00 per cent., varies in amount according to the time the metal is in contact with the carbon and the temperature at which the process is conducted. For carrying on the process, a type of muffle—or pot—furnace is used, and the raw material for the steel is packed, with the charcoal, in the pots.

Operations in the Cementation Process: This raw material is usually in the form of bars 2½ inches to 3 inches wide, ⅝ inches to ¾ inches thick, and 6 to 12 feet long. For the best grades of steel, only the best wrought iron is used, though low carbon steel made by the open hearth process may be substituted for some products. Charcoal, which has been passed over about a ¼-inch screen to remove fines, still remains the carbonizing agent, though various other substances and mixtures have been tried and used. In charging the pots, their bottoms are first covered with a layer of charcoal 2 or 3 inches thick, then, in alternation, layers of bars and charcoal are added to each until the pots are full. The bars are laid flatwise and about ½ inch apart, between edges, so that each bar is completely surrounded by charcoal. After applying the final layer of charcoal, the charge is covered with "wheel swarf,"—refuse from the grindstones,—and all openings to the pots are closed and made as nearly air tight as possible. A fire is next lighted in the furnace, and the charge, for the next 3 or 4 days, is gradually heated to a full red heat—the actual temperature varies from 800 to 1100° C.—and this temperature is then maintained for 7 to 12 days, depending upon the size of the bars used, the carbon content desired, and the temperatures attained and maintained. The degree of carbonization, or the temper of the bars, is determined by fracture tests on test bars that are withdrawn from the pots through small openings or holes provided for the purpose. When the bars have reached the desired temper, i. e., have absorbed the desired amount of carbon, the fire is banked and the furnace is allowed to cool slowly. When the contents of the furnace are cool enough to handle, the bars are removed from the pots.

Products: If the original bars were of wrought iron, their surfaces are found to be covered with irregular elevations, known as "blisters" or "beads," which result from the expansive force of the carbon monoxide formed by carbon reacting with the oxides of the incorporated slag.

Hence, these bars are known as blister steel. If the original bars were of mild steel or remelted wrought iron, these blisters are absent. Both products are frequently referred to as "converted" or "cement" steel. If air has gained access to the bars during the process, their surfaces will be covered with scale and almost decarbonized. Such bars are known as "aired bars." After sorting and reheating, the cement bars are hammered or rolled into what in England is called spring, plate, or bar steel, which formerly was used for springs, but later was used as raw material for crucible steel or for the production of shear steel. If for the latter, the bars are broken or sheared into short lengths, faggoted, sprinkled with a little borax, covered with clay, reheated to a welding temperature, and hammered into a bar, known as "single shear." For purposes requiring a high grade, uniform steel, the single shear bars are again broken at their centers, the two halves of each are laid together, and the faggot thus formed is reheated and hammered down to the required size. These bars are known as double shear steel. This steel was formerly used exclusively for the manufacture of cutlery, hence the name, shear steel.

Structure of Cement Steel: This working is necessary to obtain the highly desirable homogeneity of the steel, and, prior to the revival of the crucible process, was the only method available to attain that end. Formerly, about seven grades or tempers of shear steel were produced. These varied in average carbon content from .50 per cent. to 1.50 per cent. But as the carbon was absorbed from the surfaces of the bars, the carbon content of the blister steel bars progressively decreased to the center. In the softer grades the center portions of each bar remained unaltered, and this core was known as "sap." In the harder grades, the outside of the bar might show a carbon content of 1.50 to 2.00 per cent. with a center of .85 to 1.10 per cent. It was this characteristic of cement steel that led Huntsman, who was a clock maker, to seek a method whereby he could obtain a more uniform steel for his springs.

SECTION II.

THE CRUCIBLE PROCESS.

Principles of the Crucible Process: Realizing that the shortcomings of cement steel for springs lay in this lack of homogeneity, Huntsman conceived the idea of melting it in crucibles, which melting he thought should make the steel perfectly homogeneous. Briefly, his method was as follows: First, he carefully selected cement bars that would give the exact temper, or carbon content, he desired in the finished steel, and cut or broke these into small pieces. Then, he charged this steel into large clay crucibles, which, after covering, and luting the lids, he placed in a coke fire and heated until the contents were thoroughly fused. At this point he withdrew the crucibles from the fire, and, upon removing the

cover and skimming off the small amount of slag formed on top, he poured the molten metal into a cast iron mould, where it remained until solid. Finally, by the usual method of reheating and hammering then in use, he worked the ingot into the form desired. This method gave a steel that was not only homogeneous throughout, but was free from occluded slag and dirt, hence was so much superior to cement steel for many purposes that the method at once became the leader for the production of the finest steels. This position the process has held for almost two hundred years, and is only now being replaced by the electric process, which is cheaper, is capable of giving as good steel, and possesses many metallurgical advantages over the crucible method. Although the principles and the general method of procedure have remained the same, the process has been made the subject of considerable experimentation since the time of Huntsman, and some changes in the material of the charge, in the manufacture of the crucibles, and in the furnace for melting the crucible charges have been introduced, so that the details of standard practice for different countries and localities vary somewhat. In the following paragraphs an attempt has been made to describe the latest average American practice.

Manufacture of the Crucibles: It is evident that the crucibles, or pots, are a very important part of the apparatus required in the manufacture of crucible steel. As they are costly to make and have a comparatively short life, they are a large item of expense. In England, they are frequently made of clay by the steel manufacturer himself, but in this country so-called graphite crucibles are almost universally used, and few of the steel manufacturers make their own crucibles. These crucibles, with a capacity of 80 to 124 pounds, vary somewhat in form and thickness of wall. In general, they are barrel-like in shape, and vary in size from 13 to 18 inches in height and from 8 to 12½ inches in diameter at the bildge, outside. As to wall thickness, they are somewhat thicker at the bottom than at the top, usually about 1½ inches at the bottom and about ¾ inch at the top. Only a brief outline of their manufacture can be given here. Plastic bonding clay of the dense-burning type is dried and ground to a fine powder. During the grinding, a little sand, 10 to 20 per cent., is added, unless the silica content of the clay itself is high. The graphite is likewise ground and sized by screening, the fine dust being rejected and used for steel ladle stoppers or other articles. These materials are next weighed out in batches in the proportion of 50 to 60 parts of graphite to 40 to 50 parts of the clay mixture, and thoroughly mixed dry, care being taken to avoid any further grinding in this process. Water is now added, and the mixture is kneaded until it becomes uniformly plastic throughout. The batch is then placed in a cellar or hole, where it may retain its dampness, to age or season for several days. After curing, the batch is separated into lumps, each containing enough material for a single crucible. These lumps are again kneaded, then placed in

cloth lined plaster or metal moulds and formed by spinning on a potters jolly. The crucibles are then placed in a drying shed, and left for a day or more at a temperature but slightly (5° to 10° F.) above atmospheric. The remainder of the hygroscopic water is then driven off by heating gradually to a higher temperature for two weeks or more, when the crucibles are finally burned or annealed at about 700° C. (1300° F.), for 3 or 4 days, to drive off the combined water. To protect the crucibles from oxidation and crushing, they are usually nested with larger and smaller crucibles, and the largest crucible, unless burned in a muffle kiln, is placed in a seggar, or fire clay mould, during the burning. They are then carefully packed and shipped to the steel manufacturer. Since the crucibles are not burned to vitrification of the clayey portion, they take up moisture from the air, which is difficult to drive off. Hence they are heated, preferably to a temperature of some 150° to 160° C. for 3 or 4 days and finally to a red heat, just before they are put into service in the melting furnace. When properly made and carefully handled, these crucibles will last for several heats. One manufacturer claims to get 15 to 18 heats, but in ordinary practice 12 heats is considered as an average life for these crucibles.

The Melting Furnace in this country is generally of the gas-fired regenerative type. It consists of a number of combustion chambers or melting holes built in a row between two sets of checker chambers, as shown in the accompanying drawings of Fig. 71. Each melting hole, about three feet in depth and otherwise large enough to contain 4 or 6 crucibles, is connected with the two sets of checkers by means of short flues leading upward from its bottom. If producer gas is used as fuel, the gas checkers are placed next to the line of melting holes with the air checkers extending along the outer walls of the furnace. This plan of construction readily permits of introducing the gas into the ports below the air, which is deflected downward by the roof, thus holding the flame near the bottom of the crucibles as it sweeps across the melting hole. In case natural gas, fuel oil, or powdered coal should be used for fuel, both checkers would be used for air, or the furnace would be constructed with but one checker chamber on each side. The shop floor is built on a level with the top of the melting hole, so that only the covers are visible from above. After moving these covers aside, the crucibles are lowered into and lifted out of the hole by means of tongs with broad jaws curved to fit the crucibles.

The Bottoms of the Melting Holes are built of first quality fire brick laid on plates, which are supported by beams, or cross bars, spanning the space between the two sets of checkers, thus forming a continuous cellar, or vault, that extends the full length of the furnace beneath the melting-holes. A hole, some 4 or 5 inches in diameter, is provided in the center of the bottom of each melting hole, so that any refuse on the bottom of the melting-hole can be poked into the vault below, there to

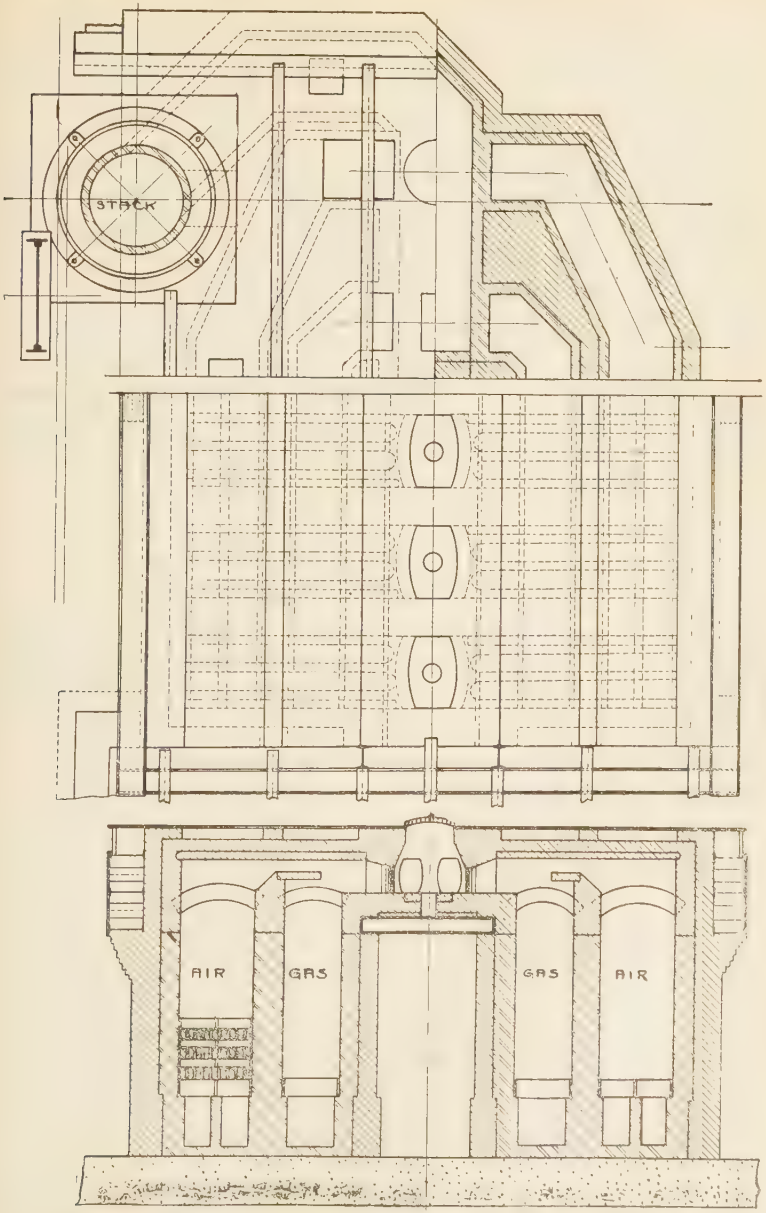


FIG. 71. Parts of Working Drawings Illustrating Construction of a Regenerative Crucible Furnace. Above, Horizontal Sections through Furnaces, Flues and Stack. Below, Vertical Section through Checker Chambers and One of the Melting Holes.

be cleaned up as opportunity affords. To protect the bottom in case of break-outs, it is covered to a depth of 6 to 8 inches with coke dust or crushed coke. This coke also gives some protection to the crucibles, as it helps to consume free oxygen not needed for combustion, and to maintain a reducing atmosphere in the hole.

The bottoms of the regenerators are provided with flues which extend in straight lines beneath the brick checkerwork, and, outside, curve into the main or stack flue. Here reversing valves and dampers are provided, which permit the two sets of regenerative chambers to be connected alternately with the stack or with the outside air and the gas supply. With this furnace, the equivalent of about one ton of coal is required to make a ton of steel, whereas, with the old style coke hole 3 to 4 tons of coke were consumed per ton of product. A flat bottom Siemens furnace similar to the ordinary open hearth, in which the crucibles are charged and drawn horizontally through the doors, has been used in some countries, but as it offers no economies or other advantages, it has received little attention in this country.

SECTION III.

OPERATIONS OF THE CRUCIBLE PROCESS.

Charging the Crucibles: From what has already been said, it will be evident that, aside from the possible elimination of gases from the steel and the separation of slag and other non-metallic inclusions, the crucible process is not a purification process. Consequently, whatever in the way of elements capable of alloying with iron is charged into the crucible will come out in the steel. On this account the greatest of care in the selection of the raw materials must be exercised. And it is characteristic of the history of the process that, once a charge that produces the kind or grade of steel desired has been hit upon by any shop, that charge is strictly adhered to and must not be varied. For many years after the introduction of the process by Huntsman, cement steel or blister steel was the only raw material used. Eventually, attempts were made to eliminate the cementation step by the use of wrought iron with charcoal; and, provided Swedish iron, which was the purest wrought iron made then, was used, the steel produced was as good as that made from cement bars. In 1801 Mushet introduced the use of manganese, by adding oxide of manganese with the charge, which practice was superseded some years later by the use of spiegel. Then followed a great deal of unsuccessful experimental work, involving so many different substances or "physics" and mixtures that the stock house came to be known as the medicine house. Later, with the introduction of the Bessemer and acid open hearth processes, efforts were made to reduce the cost by the substitution of soft steel scrap for the Swedish wrought iron, but owing, perhaps, to the fact that miscellaneous scrap was used, which carries a higher content of

manganese, phosphorus and sulphur and is more variable in composition than this grade of wrought iron, the steel was found to be of inferior quality. More recently, washed metal, that is semi-purified pig iron freed from silicon, manganese, and phosphorus, has been used with excellent results to bring up the carbon of the wrought iron. Still more recently, owing to the introduction of the cheaper electric process and the difficulty of securing good wrought iron, some manufacturers have reverted, more or less secretly, to the use of steel scrap, in part at least. With good basic or acid open hearth mill scrap, the composition of which is more uniform than miscellaneous scrap and can be more readily determined, steel of good quality can be made, provided proper care is taken to adjust the composition with the best wrought iron and washed metal.

All the practices just described have to do with carbon steels. Since the process has always been used in the production of the finest steels, especially tool steel, the introduction of alloy steels created the greatest diversity of practices. In making alloy steels the old rule of thumb methods of charging had to be abandoned for other plans in which the composition of the charge could be accurately determined by chemical analysis. This remark applies particularly to high speed tool steels, which, prior to the introduction of the electric process, could be made successfully only by the crucible process. At first, these steels were made from high grade wrought iron or muck bar by the addition of the desired elements, in the form of iron alloys, and the necessary recarburizer, in the form of charcoal or washed metal. Later, tool scrap was used to make up a part of the charge, and much inspecting and many analyses were required to select the scrap and determine the proportions of the charge.

Stages of the Process: The materials for the charge, after they have been inspected and analyzed, are sheared or broken into small pieces, then carefully weighed out in proper proportions and amounts in the mixing house. These are carefully placed in the crucibles with the base, wrought iron or steel scrap, on the bottom. The crucibles are then tightly covered and taken to the melting hole, into which they are lowered vertically by means of tongs in the hands of a workman. The gas and air are then regulated to melt the charge as rapidly as possible without injuring the crucibles. The time of melting varys from 2½ to 4 hours, according to the composition of the charge and the heating conditions of the furnace. Low carbon heats require more time than high carbons, and high speed steel requires the most time of all the other grades. When the melting of the charge is thought to be complete, the melter removes the cover from each crucible, inspects the charge and, if necessary, "feels," or stirs, the charge with a rod to make sure no particles remain unfused. As the charge melts, and for some time after melting, the metal evolves gases, which finally collect in fairly large bubbles and break slowly on the surface of the metal, producing the spectacle known as "cat's eyes." The melter now watches each pot closely, and when the steel

appears to be "dead," that is, free from gases and in a tranquil state, he signals the puller out, who grasps the crucible with the long broad tongs, lifts it out of the hole and sets it on the floor. The killing of the heat usually requires 30 to 40 minutes, sometimes longer, and is an important part of the process, because the practice is necessary to give sound ingots. On the other hand, if the steel is kept in the furnace too long after it has reached the dead melt stage, it will be injured and may be ruined by absorption of too much carbon and silicon from the crucible. The temperature is also important; if the heat is pulled too cold, the steel will begin to solidify before it can be cast, and if it is cast too hot, the resulting ingot will not be sound. In some cases the pots are pulled before the steel is completely killed, and a little aluminum (not over .02%) is added to the pot just before the steel is poured into the ingot mould.

Casting: The cover is now removed from the crucible and most of the slag is mopped or swabbed up by means of a ball of slag on one end of an iron rod. The crucible is then grasped horizontally with a pair of tongs, and, by tilting the crucible, the steel is poured into a cast iron mould. This pouring requires strength and skill, for it must be continuous, and the stream of metal must not be permitted to impinge upon the walls of the mould. Any slag that may remain on the surface of the liquid metal is held back and prevented from flowing into the mould by means of a small iron bar. The moulds are closed at the bottom, so, to facilitate the removal of the ingots after casting, split moulds are used. These moulds are cast in two pieces or halves, which, fitted together by means of rings and wedges, form a mould of square section with the joint passing longitudinally through diagonally opposite corners. Usually, the capacity of the moulds is but a single potful of steel, and their cross section is but 3 or 4 inches square; but occasionally larger ingots are required, in which case two pots may be poured at once by the use of a funnel or spout made from a worn out crucible, or several pots may be poured into a steel ladle, and the steel teemed into the moulds from it. The last plan is followed in the production of fine steel castings of a size requiring more than two pots of metal. As soon as the steel has been poured, the crucible is cleaned and carefully inspected for cracks, when, if found sound and in good condition, it is charged, as before, for another heat.

Stripping and Inspecting the Ingots: As soon as the steel has solidified in the moulds, the wedges or keys are loosened, and the rings holding the two parts of the mould together are removed. In case of lower carbon steels the mould may be removed at once and the ingot cooled in air, but ingots of high carbon and alloy steels must be cooled slowly to prevent the formation of clinks, or tiny cracks, due to non-uniform distribution of contraction and expansion forces. Such ingots are allowed to stand in their moulds till solid, then removed and placed in lime or covered with ashes or hot dry sand till cold. The ingots are then topped, that is, pieces of their tops are broken off until the fracture shows per-

fectly sound steel. From the fractures thus exposed, the temper, or carbon content (except in the case of certain alloy steels) is determined. Then they are inspected for surface defects, and carefully and slowly reheated to a forging temperature. They are next forged, or cogged, under a hammer, and any cracks or defects that appear during the forging are chipped out. After being thus forged to the required section, usually 1 to 2½ inches square, the billets are inspected again. Any surface defects, such as rough spots, seams, or tiny cracks are ground out with emery wheels, when these billets are reheated and rolled or forged into the sections desired. All this work is done with the greatest care, and is so meticulous as compared with the attention that can be given ordinary steel made in large quantities by the more modern Bessemer and open hearth processes that it is termed crucible practice. Without doubt crucible practice has played as important a part in the high quality of crucible steel as crucible melting.

Chemistry of the Process: From a chemical standpoint, at least, the crucible is the simplest of all the processes for making steel. In the beginning, the charge carries a small quantity of iron oxides in the form of rust and scale and an almost negligible quantity of free oxygen in the air trapped in the crucible. As the charge melts, these oxides form at first an oxidizing and very basic slag, which is soon reduced to the ferrous condition by the carbon in the charge or the crucible. Some of this ferrous oxide dissolves in the metal, and the remainder reacts with the clay of the crucible to form ferrous and ferrous aluminum silicates, which, after the charge has all melted and the temperature has been raised, absorb more and more silica until the slag becomes very acid. In the meantime the metal has been absorbing carbon, either from the crucible or the charcoal charged, and the conditions within the crucible now become strongly reducing. Any oxides dissolved or otherwise incorporated with the metal now react with carbon, forming carbon monoxide gas; and since the slag is very acid, silica is readily split off from the slag molecules and is at once reduced, forming silicon, which alloys with the iron and enters the metal. The absorption of carbon and the reduction and absorption of silicon both progress with time and temperature, and are more rapid in new crucibles than in crucibles that have been used. The presence of silicon in the metal has the effect of cleansing it of all oxides, and, without doubt, it is a large factor in "killing" the steel; but after a content of .50 per cent. is exceeded, it begins to have a noticeable embrittling effect upon most steels. Silicon also affects the welding and case-hardening properties adversely, hence is positively undesirable in some steels, a difficulty that many manufacturers have aimed to overcome by substituting the addition of aluminum for the complete killing. Hence, the time of killing as well as the temperature must be closely watched, but it is evident that close control of either of these factors is impossible, with the result that both the carbon and the silicon content may vary over relatively wide limits, and it is very difficult to produce steel of uniform composition in quantities of more than about a ton.

CHAPTER IX.

MODERN METHODS OF MAKING STEEL—THE BESSEMER PROCESS.

SECTION I.

CLASSIFICATION OF PRODUCTS OF FERROUS METALLURGY.

Introductory: Before beginning the study of modern methods of producing steel, it is desirable to decide the question as to what steel is. Owing to the many varieties of iron now classed as steel, a concise and wholly satisfactory definition is well nigh impossible. Attempts have been made to restrict the usage of the term, but without success, because, in defining any term, the name must be taken as it is used. Therefore, since an adequate definition of steel is lacking, a brief resumé of the commercial products of iron metallurgy may be profitable. In beginning this survey, it is to be borne in mind that the basic material for the preparation of the various refined ferrous products of today is pig iron and that this substance, a direct product of the blast furnace, represents the crudest form of commercial iron. All higher grades are products obtained by different methods of refinement, and their properties vary not only according to the method of refinement but also with the degree to which the refinement is carried. The ferrous products may, therefore, be placed under two main classes, namely, pig iron and refined iron.

Pig Iron and Cast Iron: As pointed out in Chapter VI, pig iron may vary, or be varied, very much in chemical composition and constitution. This variation gives the different grades of pig iron and determines the use to which the metal can be applied. On cooling, the crude forms first undergo a slight expansion, which is followed by a slight contraction. This fact makes it particularly suitable for mould casting, in which form it is called **Cast Iron.** Cast iron offers a high resistance to crushing, but all forms of unrefined iron are lacking in tenacity, elasticity and malleability.

Malleable Cast Iron: In the second class will be found a series of products, which may be classified according to the initial method of refinement. This refinement may be brought about in two ways,—namely, one

in which the metal remains in the solid state throughout the process and another in which the purification involves fusing the metal. Malleable cast iron is an example of the first method. Products of this class are obtained from crude pig iron of a certain composition chemically, which, upon being cast into the desired form, is subsequently subjected to a combined annealing and oxidizing process by which the malleability is developed. In carrying out the process, the clean casting is packed in iron oxide and subjected to a temperature of about 700° C. for three or more days, when it is allowed to cool in the furnace very slowly. By this treatment the greater portion of the combined carbon is converted into graphite that takes the form of very minute particles evenly distributed throughout the casting, and so does not have the weakening effect that flakes of graphite have. Some of the carbon originally present in the iron is oxidized and eliminated from the metal. It is said that a slight reduction in the sulphur content also takes place.

Wrought Iron: At present there are two classes of iron products recognized as being produced by the methods of purification involving fusion. To these are given the names of wrought iron and steel. While wrought iron, as explained in Chapter VII, may be made in different ways, the only method at present commercially practicable is the indirect process known as puddling. By this process the pig iron is first melted in a reverberatory furnace on a hearth lined with iron oxide. This treatment results in the oxidation and consequent removal, from the metal, of all but small amounts of carbon, silicon, manganese, phosphorus and sulphur. The purification brings about a rise in the fusion temperature of the iron above that of the furnace, and at this point the metal is removed from the furnace in the form of pasty balls in which more or less slag is incorporated. Some of this slag is at once removed by hammering or squeezing, after which the bloom thus produced is rolled into muck bar. In this form it may be converted into steel as noted in Chapter VIII, or it may be subjected to further mechanical treatment to produce merchant bar or double refined iron. Wrought iron, thus mechanically refined, is soft, tough, and malleable, is easily welded, and, due to the intermingled slag and the mechanical treatment it has received, is characterized by a fibrous structure.

Steel is the term applied to all refined ferrous products not included under the classes described above. It is distinguished from pig iron by being malleable at temperatures below its melting point, from malleable iron by the fact that it is initially malleable without treatment subsequent to being cast, and from wrought iron by the circumstance of its manufacture. In the case of wrought iron, the metal was in a fused state during a part of the purifying process only, whereas the purification of pig iron to produce steel takes place at a higher temperature, and the metal remains in the molten state throughout the period of purification. From a chemical

analysis it is practically impossible to distinguish wrought iron from soft steel, but the one, being obtained in a state of complete fusion and free from slag, may exhibit physical properties very different from the other, which is obtained in a semi-fused state and retains small amounts of the slag incorporated with it. Between pig iron and steel, however, a marked difference in chemical composition as well as in physical properties is observed. All three substances show a wide variation in chemical composition. The following table may be studied with profit.

Table 34. Chemical Relations of Pig Iron, Wrought Iron and Plain Steel.

	PER CENT. OF					
Name	Iron	Carbon	Manganese	Sulphur	Phosphorus	Silicon
Pig Iron.	91—94	3.50—4.50	.50—2.50	.018—.100	.030—1.00	.25—3.50
Carbon Steel..	98.1—99.5	.07—1.30	.30—1.00 (.03—.10 as tapped)	.020—.060 (.120)	.002—.100	.005—.50
Wrought Iron..	99.0—99.8	.05—.25	.01—.10	.020—.100	.050—.20	.02—.20

This table would indicate that wrought iron is not the purest form of commercial iron, as is often asserted. However, in wrought iron part of the manganese, sulphur, phosphorus and silicon shown in the table above may be derived from the incorporated slag, in which case they would exert little influence upon the metal itself.

Methods of Making Steel: Prior to 1856 it was possible to make a much finer distinction between wrought iron and steel than that indicated above. Both the shear steel and the crucible, or cast, steel produced previous to that time were manufactured from blister steel made by the cementation of wrought iron, and, while each process produced different varieties of steel, the products of both were readily distinguished from wrought iron by the fact that they could be hardened and tempered. This property was, therefore, made the basis for a definition of steel. But the introduction of the Bessemer and open hearth processes, with their numerous products, some of which can and some of which cannot be hardened and tempered, and all of which are quite different from wrought iron, necessitated a revision of this definition for steel, because, lacking a better name, the term steel was applied to the products from

the newer processes also. Then, still more recently, the advent of the electric furnace added another variety to the ferrous metals. Finally, the introduction of alloying elements has made all definitions based on the purity of the metal inapplicable. It appears, therefore, that the only general definition for steel that can be offered is one based on the method of refinement. On this basis, then, steel is a ferrous metal, produced from pig iron or wrought iron, which has been subjected to a refining process by complete fusion.

General Principles of the Methods of Purifying Pig Iron: From a commercial standpoint, the fundamental principle by which the purification of pig iron is effected is that of oxidation in all cases, excepting the electric furnace, which employs both oxidation and reduction. For the purpose of purifying by oxidation two substances are available. These substances are air and iron oxide, the application of which requires different types of apparatus. The two chief methods of purification, then, represent attempts to meet these requirements. These methods are known as the pneumatic, or Bessemer, and the open hearth, or Siemens' processes. In both, the purification may be brought about by oxidation alone, in which case they are called **acid processes,** or by oxidation in conjunction with strong bases, such as lime, when they are designated as **basic processes.** By the first class of process, only the elements carbon, silicon and manganese are removed from the iron, while the second method also removes phosphorus and, to a limited extent, sulphur. The **basic Bessemer process** has been named after its inventors, the **Thomas-Gilchrist,** and the basic open hearth is generally spoken of as the **basic**. Each of the five purifying processes mentioned above, namely, the acid Bessemer, the basic Bessemer, the acid open hearth, the basic open hearth, and the electric, produces steel somewhat different from that produced by the others, and with the exception of the electric process, each requires pig iron of a composition different from any of the others. Owing to the composition of iron ores available in this country, the pig iron produced is best adapted for treatment by the basic open hearth or the acid Bessemer process; hence, these are the leading methods employed.

Varieties of Steel: From what has been said it is evident that the word steel never has denoted a specific product. Even in the days when the cementation process was the only one in use, there were different varieties of steel. Succeeding discoveries and inventions have widened the field, or increased the number of varieties included by the term, until today it is merely a general term, or class name, for a great number of refined ferrous products. These products may be classified in three different ways, namely, according to method of manufacture, according to chemical composition, and according to use. To students not familiar with the steel industry, the following outlines may be found helpful.

Table 35. Classification of Steels.

A. **Steels Classified According to Processes and Methods of Manufacture.**

1. **Cement Steel:** Made by carbonizing bars of wrought iron or soft steel.

2. **Crucible Steel:** Made by melting in a crucible wrought iron, steel scrap, or a mixture of both, with additions necessary to control composition.

3. **Acid Bessemer Steel** (in this country Bessemer Steel): Made by purifying low phosphorus (under .090 per cent.) molten pig iron with air, and making additions, to control composition, to the purified molten metal.

4. **Basic Bessemer Steel:** Made by purifying high phosphorus (over 2.00 per cent.) molten pig iron with air in the presence of lime, and making additions, to control composition, to the purified molten metal.

5. **Acid Open Hearth Steel:** The raw materials are steel scrap and very low phosphorus pig iron (under .040 per cent.), either cold or molten. These are melted under a flame on a hearth lined with silica sand, the iron oxides formed, together with some ore added, acting as the purifying agent. Additions to control composition of the steel are added to the molten purified metal.

6. **Basic Open Hearth Steel** (in this country, Basic Steel): The raw materials are iron and steel scrap, iron ore, limestone, and pig iron of medium phosphorus content, either solid or molten. These are charged on a basic lined hearth and melted under a flame, the iron oxides and lime acting as purifying agents. Additions to deoxidize and control the composition of the steel are added to the purified molten metal.

7. **Duplex Steel:** Pig iron of medium high phosphorus content is partially purified in an acid Bessemer converter, then transferred to a basic open hearth, where the purification is completed and the metal converted into steel as in No. 6.

8. **Electric Steel:** In this country the raw materials are usually steel scrap or molten metal purified by the acid Bessemer or the basic open hearth process, but pig iron or pig iron and scrap may be used. Heat generated electrically keeps the charge molten while it is being purified with oxidizing and reducing slags, and during the additions necessary to control the composition.

B. **Steels Classified According to Composition:**

I. **Plain Steels:** Steels in which the only solid elements are iron, carbon, manganese, silicon, phosphorus, and sulphur.

1. **Ingot Iron:** Highly refined steel made in the basic open hearth furnace, consisting of almost pure iron and containing a maximum of .15 per cent. total impurities.

2. **Simple Carbon Steels:** Steels in which carbon is the only element employed to control physical properties, but they may contain some manganese (less than 1 per cent.), with a minimum of other impurities. They may be divided into two main classes.

a. **Hypoeutectoid Steels**—Steels containing less than .85 per cent. of carbon. These steels may be and are roughly divided as follows:

i. **Dead Soft Steels:** Made in the basic open hearth and contain less than .10 per cent. carbon and from .20 to .50 per cent. manganese.

ii. **Low Carbon Steels:** Contain from .10 to .30 per cent. carbon and less than .60 per cent. manganese. May be made by the Bessemer, the open hearth, the duplex, or the electric process.

iii. **Medium Carbon Steels:** Contain from .30 to .85 per cent. carbon and less than 1.00 per cent. manganese. May be made by any of the processes mentioned under ii or by the crucible process.

b. **Hypereutectoid or High Carbon Steels:** Steels containing more than .85 per cent. carbon. These steels seldom contain more than 1.50 per cent. carbon nor more than .40 per cent. manganese. They are made by the crucible, open hearth and electric processes.

II. **Alloy-treated Steels:** Carbon steels to which some other element or elements are added to improve their quality, but without changing markedly their characteristics. They are generally of the low carbon and medium carbon types, and are usually made by the open hearth, Bessemer, or electric processes. The elements that may be added for this purpose, in addition to manganese, are small amounts of aluminum, silicon, titanium, copper, phosphorus, sulphur, chromium, molybdenum, vanadium, and tungsten.

III. **Alloy Steels:** Steels, which, in addition to carbon, contain another element or other elements in sufficient amounts to modify the properties to a marked degree over the carbon steel. They may be divided into the following groups:

a. **Simple Alloy or Ternary Steels:** Steels that contain but one other alloying element in addition to carbon.

1. Low Manganese Steel—Steels containing over 1.00 per cent. and less than 7.00 per cent. manganese, made by the acid or the basic open hearth or the electric process. Used as structural steels for machines and for some tools.
2. Manganese Steel—Steels containing more than 7 per cent. manganese. Made by acid open hearth or electric processes, used in railroad crossings, frogs, switches, etc.
3. Silicon Steel—Steels containing from .50 to 4.50 per cent. silicon. Made by basic open hearth or electric processes, used in electrical machines and apparatus.
4. Nickel Steel—Steels containing more than .5 per cent. nickel, usually made by basic open hearth process. Used mainly as structural steels.
5. Chrome Steels—Made by basic open hearth or electric processes, but can also be made by crucible process. Used in forging steels, for tools and other special purposes. The chromium content is usually over .50 per cent.
6. Molybdenum Steels—Made mainly by the basic open hearth process. Used occasionally in structural steels and parts of machinery. The molybdenum content is between .40 and 1.00 per cent.
7. Vanadium Steels—Made mainly by basic open hearth and electric processes, and also by the crucible processes. Used in fine steels for tools and machinery. The vanadium content is generally .15 to .25 per cent.
8. Tungsten Steel—Made mainly by electric process, but can also be made by the crucible process. Used mainly for magnets. Tungsten content 3 to 7 per cent.

b. **Quarternary Steels:** Steels that contain two alloying elements in addition to carbon. The chief representatives are:

1. Chrome-Nickel Steels—Mainly structural steels made by basic open hearth process.
2. Chrome-Vanadium Steels—Used mainly for fine forgings and parts of machines. Made by basic open hearth and electric processes.
3. Chrome-Molybdenum—Fine structural steels for parts of machines. Made by basic open hearth and electric processes.

III. **Alloy Steels—Continued.**

c. **Complex Alloy Steels:** Steels that contain more than two alloying elements in addition to carbon. These steels are generally high grade, high priced steels designed for certain special purposes, and include a great many varieties. The chief representatives, however, are the high speed steels, which are chrome-tungsten - vanadium, or chrome - tungsten - vanadium - cobalt steels for tools.

C. **Steels Classified According to Use:** In former times the different varieties of steel were largely classified by use, but its uses have now been extended to so many fields and the varieties have increased to such an extent that such a classification is now well nigh impossible. However, this custom survives to some extent, so that an understanding of the significance of some of the terms most commonly met with is desirable. Among these may be mentioned the following:

1. **Structural Steel:** Used in the fabrication of buildings, bridges, ships, cars, and other structures, mainly low carbon steels, but includes many varieties of alloy-treated and alloy steels. Made chiefly by the open hearth process.

2. **Tool Steel:** Any steel adopted to the manufacture of hand or machine tools. Many varieties, including medium and high carbon plain steels and many classes of alloy steels. Made mainly by the crucible and electric processes, but common grades are also made by the open hearth process.

3. **Spring Steel:** Any steel suitable for the manufacture of springs, such as those used on cars, carriages, automobiles, etc. Includes medium and high carbon plain steels, and quarternary alloy steels. Made by open hearth and electric processes.

4. **Boiler Steel:** A high grade low carbon steel especially adapted for use in making boilers. Made by the open hearth processes.

5. **Rail Steel:** Any steel suitable for railroad rails. Usually .60 to .85 per cent. carbon steel made by the basic open hearth process, but some rails are still made by the Bessemer process, in which case the carbon ranges from .30 to .60 in different grades.

6. **Pipe Steel, Skelp Steel, or Welding Steel:** A dead soft or low carbon plain steel especially suitable for welding. Made by the Bessemer and open hearth processes.

C. Steels Classified According to Use.—Continued.

7. **Sheet Bar and Tin Bar:** Any steel suitable for rolling into sheets. Mainly low carbon steels made by the basic open hearth or the Bessemer process, but some is also made by the acid open hearth process.
8. **Case Hardening Steel:** Any steel that can be carbonized or case-hardened readily. Low carbon plain steels or ternary or quarternary alloy steels. Made mainly by the basic open hearth process, but some grades are made by the electric process.
9. **Electrical Steel:** Usually silicon steels used in the manufacture of electrical machines and apparatus.
10. **Strip Steel:** Any steel rolled into the form of strips. May be hot finished (hot rolled strip) or cold finished (cold rolled strip). Made mainly by open hearth process.
11. **Hoop Iron:** Low carbon steel in strip form suitable for hoops. Made by basic open hearth or Bessemer processes.
12. **Free Cutting Steel:** Steel for bolts, nuts, screws, etc., that machines readily. Made by Bessemer or open hearth processes.
13. **Forging Steel:** Steel especially suitable for forging, that is, hammering or pressing. Usually medium carbon plain steel or quarternary alloy steels. Made by basic open hearth or electric processes.
14. **Cast Steel:** A term used in connection with any article of steel formed by casting.
15. **Forged Steel:** A term applied to articles of steel formed by hammering or pressing.
16. **Wrought Steel:** A term used in connection with any article of steel formed by forging or hot rolling, or by hot working in any way.

SECTION II.

PRINCIPLES AND HISTORY OF THE BESSEMER PROCESS.

Principles of the Process: Of all the processes for the purification of pig iron, the Bessemer is the simplest. Essentially, it consists of blowing air under pressure through a bath of molten metal contained in a vessel constructed of proper refractory materials, whereby a portion of the iron, all of the silicon and manganese, and then the carbon are successively oxidized. The first three elements, upon combining with oxygen, go to form a slag, while the carbon is eliminated in the form of the gases, carbon-monoxide, CO, and carbon dioxide, CO_2. As noted elsewhere, the

oxidation of these elements are exothermic reactions from which the heat required to maintain the metal in the liquid state is derived. Since steel produced in this way, without recarburization, contains deleterious oxides which render it unfit for use, it is necessary to add deoxidizers to the metal after blowing. This fact was not realized at first, and the history of the process serves to emphasize its importance.

Some Incidents Connected with the Early History of the Process: The history of this process also furnishes an example of the way in which a method is developed, and illustrates the fact that the perfecting of a process is seldom accomplished by one mind alone, but by many minds thinking toward one goal. The method was almost concurrently, but independently, originated by two men: one, an American named Wm. Kelly of Eddyville, Ky.; the other, an Englishman, the illustrious inventor, Henry Bessemer. Although Kelly did not apply for patents until 1857, almost two years after Bessemer's English patent was granted, his application was allowed on grounds of priority, because he was able to prove that he had worked out the idea as early as 1847. In the same year that he made application for patents, Kelly erected a tilting converter for the Cambria Steel Works at Johnstown, Pa. This vessel is still preserved. Lacking financial means, however, Kelly was unable to perfect this invention, and after much litigation with the Bessemer interests, a settlement was made, whereby Kelly dropped out of the game. Bessemer, on the other hand, in addition to conceiving the idea and putting it to trial, continued his experiments in the face of great difficulties and many failures until he had brought the process to a high degree of perfection. At first, Bessemer accidentally employed only Swedish iron, which had a low phosphorus and a high manganese content, and was very successful in converting it. Then, it having been adopted by many manufacturers, the process failed when applied to English irons which were high in their phosphorus and low in their manganese content, and prejudice and opposition to the method became so great among steel makers that, in order to save his process, Bessemer was obliged to build a steel works himself. His plant, built at Sheffield, began to operate in 1860.

Importance of Manganese: At the Sheffield works the process was used at first to produce high carbon steels from Swedish pig iron only, because low carbon steels, obtained by subjecting the metal to a full blow, were almost invariably hot short, even when made from the excellent Swedish iron. This defect was later overcome by the addition of manganese in the form of spiegeleisen, the beneficial effects of which were first recognized by R. Mushet as early as 1856. With the adoption of the use of manganese, mild or soft steels produced by the process came into so great demand that the former practice in blowing was abandoned in England, though it is still employed in Sweden. The first Bessemer plant in this country was erected in 1867.

Thomas and Gilchrist: The removal of phosphorus by the use of a basic lining and the addition of lime to the bath was first conceived by Thomas, who made known the success of his scheme in 1878. In the development of this process, Thomas was assisted by his cousin, the chemist Gilchrist, hence the name Thomas-Gilchrist.

Other Improvements: While the process was highly developed along mechanical lines by Bessemer, himself, it remained for Alexander Holley, an American Engineer, to introduce many improvements in the erection of Bessemer plants. The most important of these was his invention of the detachable bottom, which will be described later. Another important invention was that of the hot metal mixer, since it furnished a ready supply of molten metal of fairly uniform composition, thus allowing the process to be operated much more rapidly and economically. This vessel, also to be described later, was the invention of W. R. Jones of the Carnegie Steel Company's Edgar Thomson Plant at Braddock.

Plan of Study: Before beginning a more minute description of the process as it is carried on with these modern improvements, it is well to note that the details of the operation will vary much in different plants as well as in different countries. The description, therefore, must be either very general in character, or be restricted to some one plant which will suffice as an example for all. For the present purpose, it is best to follow the latter course, and the Carnegie Steel Company's plant at the Edgar Thomson Works is selected to serve as such an example. General features of great importance may then be introduced in connection with the discussion of the various topics. At these works, the product from eleven modern blast furnaces is available to supply both the open hearth plant of sixteen 90-ton furnaces and the Bessemer plant of four converters, the maximum capacity of each of which is twenty tons.

SECTION III.

EQUIPMENT AND ARRANGEMENT OF THE EDGAR THOMSON PLANT.

The Converter House: The four converters are arranged in a row along one side of the converter building, which is located in one corner of the works in close proximity to the rail mills. The converters, being of the concentric type, tilt in two directions, in one direction for charging and in another for pouring. On the charging side of the vessels the building is erected three-story fashion. The ground floor extends under the converters and offers space for the removal of bottoms, slag, etc. The second floor, designated as the charging floor, is on a level with the trunnions. From this floor all molten materials are charged into the vessels. From the third floor, called the scrapping floor, all cold materials are charged. Serving the four converters on the pouring side, are two jib cranes for handling the steel ladles into which the metal is poured after

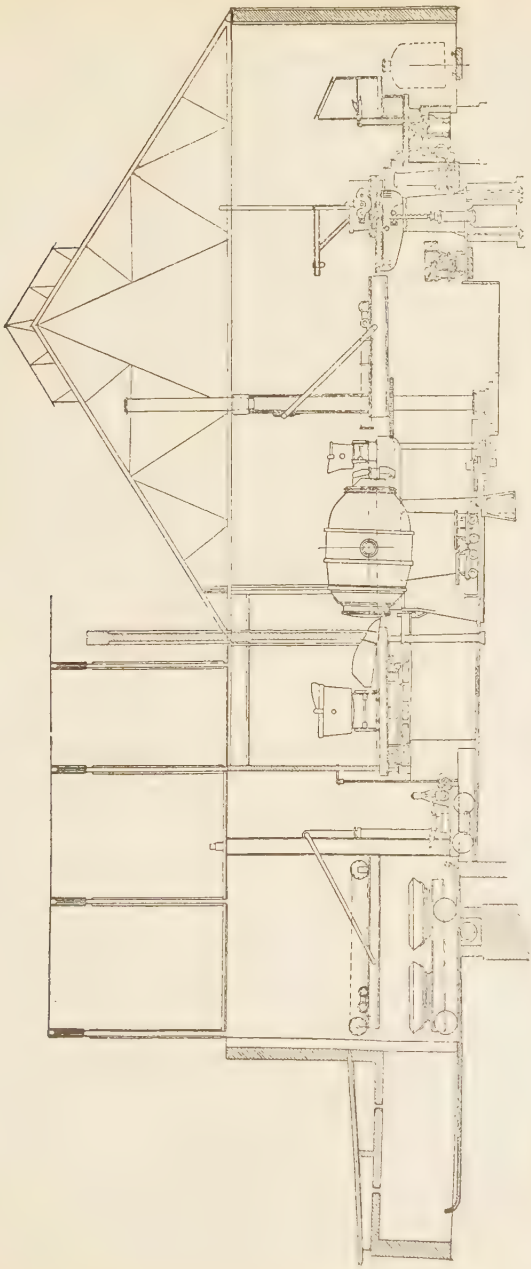


FIG. 72. Cross Section of a Converter Plant.

each blow. These cranes may be swung around so as to deliver the steel to stationary teeming tables located in front of the teeming platform which extends along the side of the building opposite the converters. Between this platform and the tables, which support the ladles during the teeming process, is laid a narrow gauge track, along which the ingot moulds, set upon small cars, are moved during and after the teeming. This motion in front of the platform is imparted by means of dogs attached to three hydraulically operated cylinders that lie between the rails of the tracks. All the operations of the converters and jib cranes are controlled from a pulpit located at the side of the building opposite the converters and above the teeming platform. Just back of the converter building and inter-communicating with it through an open side beneath the charging floor, is the **bottom house,** equipped with over-head cranes and buggies for handling bottoms. Here the frequent repairs to bottoms are made. As these repairs must be made with wet refractories, new bottoms require thorough drying before being put into service. For this purpose six **drying ovens,** each large enough to contain two bottoms, are provided. Built against one end of the converter house, like the wing of a building, is a cupola house. It also is inter-communicating with the converter building on its charging floor. In the angle formed by the cupola and bottom houses are kept the stores of cold pig iron, spiegel, and ferro manganese, while beyond these will be found a building in which is housed suitable rock crushing machines and Chilean mills for crushing and mixing the refractory materials used in making up the various mixtures required for bottoms and repairs about the plant.

The Larger Accessories: The cupolas, blowing engines, mixers and strippers, are each separately housed and are located at various distances from the converter house. All these accessories play a very vital part in the process and in the operation of the plant, hence are deserving of special consideration.

The Cupolas: In former times, when converter plants were operated as independent units, detached and far removed from the blast furnaces, cupolas were used to melt the cold pig iron preparatory to charging. At this plant furnaces are used only for melting the pig iron and spiegel mixtures employed as recarburizers. In construction a cupola is cylindrical in shape and resembles a miniature blast furnace. Those at Edgar Thomson Works are eight feet in diameter outside and some twenty feet in height, measuring from the mantle to the charging doors. Like the blast furnace, there is an opening at the bottom of the hearth for tapping out metal and another for slag. Above these openings are inlets for ten tuyeres, through which cold air, under a pressure of six to ten ounces, is blown by fans. Near the top are the two large openings or doors for charging, directly opposite each other and opening upon the charging floor. A little above these openings, a contraction of four or five feet in the outside diameter of the

shaft forms the stack, also about twenty-four feet high, for the escape of gases. The entire furnace rests vertically on a mantle which is supported by a number of columns fixed upon a firm foundation. This construction permits the use of the drop bottom, which facilitates the removal of worn-out linings, the frequent repairing required by the lower lining, and the rapid discharge of the stock in case of emergency. For the sake of economy, the lining, or wall, is made of different materials. The upper wall, for a distance of about four feet below the charging doors, is made of fire brick and is nine inches thick. Below this brick work, the wall is built of firestone and is gradually increased in thickness, forming a kind of bosh above the hearth, the walls of which are about eighteen inches thick. No attempt is made to cool these walls, so it is customary to back up the firestone of the hearth-wall with fire brick in order to safeguard the steel shell. The shell, like that of the blast furnace, supports and re-enforces the masonry. It is made of steel plates, which are riveted together.

Charging the Cupola: The cupola charge is composed of coke, spiegel and pig iron, in alternate layers of metal and coke, to the last of which is added sufficient limestone to flux the ash. When the orders call for steel with a high content of silicon, ferro-silicon is also added to the charge. The ratio of coke to metal varies a little. At all times the amount of fuel will be as small as possible, both for the sake of economy and to exclude sulphur and phosphorus, which are absorbed by the metal, as much as possible. Sulphur in the charge does not result in a rise in the sulphur content of the molten spiegel, but in a waste of the manganese, which reacts with the ferrous sulphide to form manganous sulphide, and goes off with the slag. Ordinarily, the coke will be about 8 per cent. and the stone about 2½ per cent. of the metallic charge.

The Blast: Just outside the converter house, on the pulpit side, is the blowing room. Here are located three steam blowing engines of the compound vertical type, which create the air blast for the converters. The blast from these engines is delivered into a common main, through which it is conducted into the converter building, where it is distributed through a manifold to lines leading separately to the four vessels. The admission of air to the vessels and its pressure are nicely regulated by a system of valves under the control of the blower. Thus, the pressure on the main is maintained at about 25 pounds per square inch by means of a blow-off valve, which is used to regulate the pressure while the vessels are charging or pouring. In case some of the converters are not being operated, one or more of the blowing engines is stopped. By means of a second valve, operated from the pulpit by a screw control, a pressure of 18 to 20 pounds per square inch is maintained on the line leading to each vessel. Under this pressure the blast may be almost instantaneously admitted to or shut off from the vessel by means of a third valve of the butter-fly type. A fourth valve provides a means by which steam may be admitted to the

blast line as required. The limits of blast pressure to the converter are about 10 and 25 pounds per square inch. The lower pressure is just about sufficient to keep the metal out of the tuyeres in a normal charge, while if the higher pressure be exceeded, large amounts of metal are blown out of the converter.

The Mixer: The supply of molten pig iron is obtained from a hot metal mixer plant of two mixers, located at one end of the open hearth house and about one hundred yards from the converter mill. These mixers are large cylindrical vessels each constructed of steel plates riveted together to form a shell, which is lined with silica brick or a good grade of fire brick. The vessel is mounted upon two sets of racers and rollers as shown in Fig. 79, page 297, which in turn are set upon firm foundations of concrete. Upon these racers and rollers, the vessel is rotated about its central axis by means of an electric motor connected through reduction gears to a large screw, which actuates the vessel through a connecting rod attached to its bottom, as shown in the figure. The molten iron from the blast furnaces is conveyed to the mixer in tipping ladles, from which the metal is poured, by means of an electric crane, into the mixer through an opening at one end of its top segment. In the diagonally opposite end, another opening, provided with a spout, permits the drawing off of the hot metal as required by merely tilting, or rolling, the mixer. In drawing off metal, the receiving vessel is placed upon a scale platform, which permits the metal to be weighed with a fair degree of accuracy. These mixers are each provided with a gas burner at one end, but very little heat above that held by the metal is ever required to keep the contents molten.

Importance of the Mixer: The hot metal mixer is almost indispensable to a modern Bessemer plant, or for that matter, to any steel making plant. Primarily the mixer serves as a storage place for the hot metal from the blast furnace, and in performing this function bestows great benefits. Thus, not only is the heat from the hot pig iron conserved, but the metal delivered to the vessel, or vessels, is of a more uniform composition than could be otherwise obtained. Again, since the capacity of the modern mixer permits it to contain casts from several furnaces, iron low in some elements may be mixed with some that is high in the same ingredients; and so it is possible to extend the chemical limits of the iron receivable. Mixers have been constructed of various shapes and sizes. Their capacities will range from 150 to 1300 tons, but the tendency in all modern construction is toward the larger size. Purification of the metal is said to take place to a slight extent in the mixer, sulphur being the chief impurity removed. The reduction in sulphur, however, is only noticeable when the manganese content of the iron is high. In the case of iron made from Lake Superior and Birmingham ores, this removal is at all times so small as to be of minor importance.

The Stripper: One of the most efficient and economical inventions contributed to the steel business is the stripper. As its name indicates,

it is a device whereby the moulds are pulled, or stripped, from the ingots after the metal has cooled sufficiently to form a solid shell on their outside surfaces. Those at the Edgar Thomson Works are of a late type and are electrically operated. A stripper of this type is in the form of a strong over-head crane, from which is suspended a vertical arm, provided, in place of a hand, with two jaws that fit over lugs cast on either side and near the top of the mould. Operating between the jaws is a ram, or plunger, capable of exerting pressure on the top of the ingot, while it is being stripped, sufficient to balance the pull. In stripping an ingot, the jaws engage the lugs and exert a powerful pull upward, while the ram, having been inserted through the top of the mould, holds the ingot on the stool till the mould is loosened. The mould is then raised high enough to clear the ingot and placed upon an empty car standing, ready to receive it, on a track next and parallel to that on which the stripped ingot stands. Electric strippers, owing to the fact that they are travelling, possess a decided advantage over the older type of hydraulically operated machines, which are stationary.

The Casting Equipment includes the teeming ladles, ingot moulds, stools, and cars. **The teeming ladle,** which acts as a container for the finished steel while casting, is a large cup-shaped vessel made of steel and lined with a few inches of "ball stuff." As slag is liable to spoil the ingots if allowed to flow into the moulds, steel cannot be poured from a vessel by tipping, but must be teemed from a small hole in the bottom. For opening and closing this hole, the vessel must be fitted with a stopper that can be operated from the teeming platform. This stopper consists of a steel rod, protected with fire-clay sleeves, to the lower end of which is fastened a stopperhead, made of plumbago bonded with clay, that fits neatly into a nozzle placed in the bottom of the ladle. The upper end of this stopper is fastened to a goose neck that fits over a vertical sliding bar attached to the outside of the ladle. This bar is provided with a lever by which it may be raised or lowered, causing a like movement of the stopper. To guard against a leaking, or "running," stopper the nozzle may be filled with dry sand or loam, which is held in place by a sliding plate on the outside. When the ladle is ready to teem, this sand is easily punched out of the nozzle after removing the plate.

The Ingot Moulds into which the finished metal is teemed are made of cast iron and may be of almost any convenient form and size to suit the respective blooming mills. At these works, the standard moulds are about 6 feet high, have a square section of 23⅝ inches at the bottom, with corners slightly rounded, and taper sufficiently to allow the mould to be stripped readily from the ingot. The moulds are open at both ends, and, when ready for teeming, rest, big end down, on heavy cast iron plates, called **stools.** The stools are mounted in twos on small cars, or buggies, which are so constructed that their sides form aprons that protect both the track on which the cars run and their own running gear from splattering by hot metal during the teeming of the metal from the steel ladle. The care of the moulds is

very important, since defects here are very likely to show up in the finished material after rolling. Their sides must be kept smooth and clean, and the teeming must be done so as to avoid splattering their sides, if possible. After being stripped, the moulds are inspected and, if their condition is satisfactory, may be used again. So, after cooling to a point where the hand may be held against them, they are cleaned, and the tops are sprayed, outside, with a clay wash to prevent the steel splashings from sticking. Then the moulds are marked, inside, with chalk for size of ingot required. None of the wash should be permitted inside of the mould, as it may become a source of dirt in the steel. As soon as the clay wash is dry, the mould is ready to receive the molten steel. Usually, about seventy ingots may be cast in one mould before it is scrapped.

SECTION IV.

CONVERTER CONSTRUCTION AND REPAIRS.

General Features Pertaining to Converters: As to the form and size of converters, methods of admitting the blast, and removing the steel after blowing, there are several possible arrangements, and converters have undergone many modifications. Thus, as was originally the plan, the air might be admitted horizontally through the wall of the vessel near the bottom, in which case the vessel would be of the **side-blowing** type; or a blast of air will be forced upward through openings in the bottom of the vessel, to which method the term **bottom blown** is applied. To facilitate the charging of materials into the vessels and the removal of metal from them, converters are now always constructed so that they may be rotated on their shorter axis through arcs of varying size. Such converters are of the **tilting** type. The first vessels were of the **fixed** type, the metal being tapped through a hole in the wall at the bottom. In both size and shape, vessels still vary much. The capacity will range from 5 to 25 tons. The vessels at Edgar Thomson are 11 feet in diameter, outside and measured along their axis of rotation, and almost 18 feet long. As to form, converters were at first somewhat pot-shaped. Attempts to design vessels that would retain heat and prevent the ejection of materials has led to two general forms, each with its own advantages. In both forms the upper diameters are shortened, forming the **nose** of the vessel and leaving a small opening in the top, which forms the **mouth.** The body may retain the form of the cylinder, as in the **straight-sided** type, or be narrowed at the bottom also, in which case the body has a **curved** contour and somewhat resembles an egg in shape. The mouth may be located at the top **concentric** with the bottom and in a plane parallel to it, as shown in Fig. 72, or it may be placed to one side, as shown in Fig. 73, in which case the opening lies in a plane at an angle to the bottom and is then called **eccentric.** The vessels at Edgar Thomson Works are all of the bottom blown, curved body, tilting, concentric type.

Parts of Converter: For convenience in constructing the vessel to allow for contraction and expansion and for making repairs later, these

FIG. 73. View of an Eccentric Converter. About three minutes after charging.

converters, as are all bottom blowing types, are constructed in three separate parts, known as the **nose**, the **body**, and the **bottom.** The shell for each of these parts is made of heavy steel plates, all firmly riveted together. The nose section is bolted to the body, but the bottom is held in place against the lower edge of the body by linked key bolts. The links of these key bolts fit over lugs on the body, while the key bolts themselves fit between lugs on the bottom, making it easy to key the two parts firmly together. When it is necessary to replace an old bottom with a new one, the keys can be very quickly knocked out or driven in with sledges in the hands of the workmen. The shell for the body is, itself, made up of three parts, known as the nose section, the journal section, and the shoulder section. The journal section is made up of a heavy band to which the two trunnions that support the vessel are attached. All these parts are firmly bound together by a great number of long key bolts attached to the shoulder and nose sections, respectively. The trunnions rest on bearings in a frame work which is supported by cast iron columns. On the end of one of the trunnions, both of which are hollow, is the connection, made through a packed joint, to the blast line. From capped openings on this same trunnion between the bearing and the vessel, a copper goose neck leads to the bottom of the vessel, thus forming a continuous passage for the blast from the main, which is stationary, to the wind box, which must move with the bottom of the vessel. To the other trunnion is attached a pinion which meshes with a toothed rack that slides horizontally. By means of a double acting hydraulic cylinder, the piston of which is connected to this rack, the vessel may be rotated through an arc of 270°, the pinion and rack being geared so that the vessel may be completely inverted for dumping slag or relining the vessel. All this mechanism is carefully covered to protect it from slag, dust and other dirt.

Lining of the Converter: The lining for the shell may be composed of any first class silicious refractory material. At most works a highly silicious sandstone, known as firestone, is used, while a mixture, composed of about five parts crushed ganister and one part best quality fire clay and called ball stuff, serves as a kind of mortar. The lining varies in thickness from ten to sixteen inches for the different parts of the vessel, being thickest on those parts subject to the greatest wear. When lining a new vessel or relining an old one, the bottom is detached, the vessel is inverted and the lining is begun in the nose. The method pursued in starting the lining will then depend largely upon the materials available and the shape of the vessel. At the Edgar Thomson Works, the customary procedure is as follows: A wooden frame, some five feet square and with a hole in the center of the same shape and size as the mouth of the vessel, is laid on suitable cross pieces and then suspended from the vessel so as to press firmly against the nose and in such a position that the hole is superimposed upon the mouth. In this way a ledge upon which to begin the wall is formed. Upon this ledge is placed a three-inch layer of ball stuff, which is followed by a

course of large, flat, undressed firestone, set in on edge. All the interstices are rammed full of wet ball stuff, so that the stones are securely keyed into place and the side and top present a smooth surface. Upon this nose wall, which is about sixteen inches thick and thirty inches high, the body wall is built. It consists of two courses. A thin course of split brick is laid next to the shell, while within this, the inner course, about twelve inches thick, is built up of rough blocks of firestone laid in a mortar of ball stuff. The stones for the top course of this wall are cut to shape and keyed in so as to hold the wall in place when the vessel is righted and also to form a smooth joint, or shoulder, against which the bottom is to fit. The lining is now completed by plastering the interior of the vessel with ball stuff, after which it is carefully and thoroughly dried. The coat of plaster, aside from giving a smooth surface, protects the stone and overcomes its tendency to spall. To prepare the vessel for use, the bottom is put on, the vessel is inclined, and then heated to a high temperature with natural gas fires in the vessel itself. In case of a shortage or absence of gas, coke or wood may be substituted for the gas. With careful patching this part of the lining may last for several weeks, or even months, of continuous running.

The Bottom of the converter warrants special mention. It is the part of the vessel subject to the greatest wear, and seldom lasts longer than twenty heats, when it must be removed for repairs and replaced by another. This change can be made with a delay of less than twenty minutes, and is carried out in the following manner: The bottom of the wind box is removed while the vessel is pouring, then, as soon as the slag is dumped, the converter is righted, and a small but strongly built truck provided with a hydraulic jack, or lift, is run beneath it. The water connection having been made with the hydraulic cylinder, the pressure is applied to the jack, which raises a small table against the bottom. In some plants the jack is placed beneath the track, in which case the whole truck is raised. The keys are next knocked out, which leaves the bottom free to descend with the table or the truck. The truck is then pulled into the bottom house, where an overhead crane picks up the bottom and carries it to one side. By reversing this procedure, a new bottom is soon in place, and the converter is ready for charging.

Relining the Bottom: The repairing of the old bottom is immediately begun. What remains of the old tuyeres and filling is quickly cooled with water, and that on the bottom is loosened with suitable tools, when it may be removed from the bottom by dumping it with the crane. The removal of this material makes it easier to inspect the construction of the bottom. The shell is made of heavy steel plates riveted together in the shape of a shallow bowl with an open bottom. Closing this opening from within the bowl, is the false bottom, a flat circular casting, with openings through which the tuyeres may be inserted. It is a little larger in diameter than the opening which it closes, thus making it unnecessary to fasten it in any

way. It supports the bottom stuff in which the tuyeres are packed. Covering this same opening from without is the tuyere plate, a similar casting containing bevelled openings into which the tuyeres fit when in place. This plate is prevented from making a tight joint with the bottom by means of the splice plates that hold the riveted plates together. Thus, an open space about one inch in depth is left between the tuyere plate and the false bottom. The plate forms the top of the wind box, the two being firmly bolted to each other and to the bottom with the same bolts. The side of this wind box is a large casting, oval in shape, and about twelve inches in depth. The bottom of the box is a steel plate which is firmly keyed to the casting to make an almost air tight joint when the vessel is blowing. Connecting the wind box with the interior of the bowl, are nineteen to twenty-one circular bevelled holes, through which the tuyeres are inserted. The tuyeres are cylindrical bricks, flared for a distance of about six inches from one end. They are about thirty inches long, seven inches in diameter, and each one contains about twelve holes, one-half inch in diameter and extending longitudinally. To place a tuyere, the flare is covered with a mortar, composed of fire clay and Portland cement, and the tuyere is inserted upward through the opening in the bottom, where it is held in place with clamps until the filling has been put in. When all the tuyeres have been thus placed in position, the top of each is covered with a metal plate to keep dirt out of the tubes, some bottom stuff is placed on the bottom in the space around the tuyeres, and on this large tiles are set in as reinforcement to the tuyeres. The space remaining about the tuyeres and brick is then tamped full with more of the bottom stuff, which is a moist mixture composed of 28 parts crushed ganister, 12 parts blue fire clay, 3 parts ground brick bats, 3 parts old bottom stuff and 4 parts coke dust. The bottom is then pushed into a drying oven, fired with coke oven gas, and carefully dried, then finally baked for several hours. The time required to dry and bake a bottom properly is about forty-eight hours, though bottoms will often be used at the end of thirty-six hours. Upon being required for use, it is withdrawn from the oven, and a heavy layer of a stiff clay mixture is placed around the upper edge to form a tight joint with the shoulder of the vessel when the bottom is in place. The mortar is then sprinkled heavily with coke dust, after which the bottom is put into service as previously described. The function of the coke dust is to prevent the bottom from cementing itself to the shoulder joint. When in service the position of the bottom is such that the long axis of the oval wind box is parallel to the axis of rotation of the vessel. The advantage of this shape is obvious, for it is easily seen that with the wind box in this position a greater volume of metal may be held in the vessel while in the horizontal position without filling the tuyeres than would be possible with a round box, which is the form used on eccentric vessels. The double bottom, mentioned above, is also of great advantage. Since the space between the upper and lower plates connects with the outside, it not only gives warning of a worn out tuyere, but also prevents the wind

box from being filled with hot metal in case of a break out. When a tuyere becomes defective or badly and dangerously worn during a blow, it may be plugged by turning the vessel down, removing the wind box lid, and stopping its openings with clay.

SECTION V.

THE CONVERTER IN OPERATION—PURIFYING THE METAL.

Charging the Vessel: With the bottom fastened in place and the vessel at the proper temperature, it is ready for the charge. The charging is a matter of much importance. Besides being a factor in determining the composition or grade of steel produced with respect to phosphorus and sulphur, it also offers a means of controlling the temperature during the blow. It must always be predetermined by the blower, who has charge of the blow. In acid practice the charge consists of molten pig iron, to which is added cold pig iron or steel scrap in amounts sufficient to meet the heat requirements of the blow. As the only source of heat is the oxidation of the iron, silicon, manganese and carbon, the composition of the pig iron is important, and the blower must be kept informed in advance as to the composition of the iron. In operating a hot vessel on hot iron there is much more heat generated than is required to keep the metal molten, in which case the temperature may be kept under control by charging steel scrap. Scrap may be added to the heat at any time during the first part of the blow. The addition of scrap also has the advantage of increasing the output. In beginning on a new lining or a new bottom, or after a delay, the vessel will be cold and will, itself, absorb much heat, which condition precludes the use of cold materials in the charge. In an attempt to lessen the loss of iron through oxidation and shorten the time of a blow, roll scale or other oxides of iron are often charged. Such additions may reduce the blowing period by about one-third, and are made regularly at some plants, but this is not the practice at Edgar Thomson. On making a steel that requires a high sulphur content, like screw steel, the required amount of this element, in the form of pyrite, may be added along with the molten metal. The blower, having been informed as to the requirements of the rolling mills, decides upon the charge best suited to the conditions, then sends an order to the mixer for a certain weight of pig iron. At these works this amount will vary from 30,000 to 36,000 pounds. The molten iron is weighed at the mixer as it is poured into the ladle, the truck of which sets on a scale platform. Some coke breeze is then thrown upon the molten metal to keep it from skulling the ladle, when it is taken by a dinkey to the charging floor of the converter. Here, the vessel is turned down to a horizontal position, so as to bring the tuyeres well above the bath, and the molten iron is poured into the mouth of the vessel by slowly tipping the ladle. The scrap is added from the scrapping floor shortly after the vessel is brought to the vertical position.

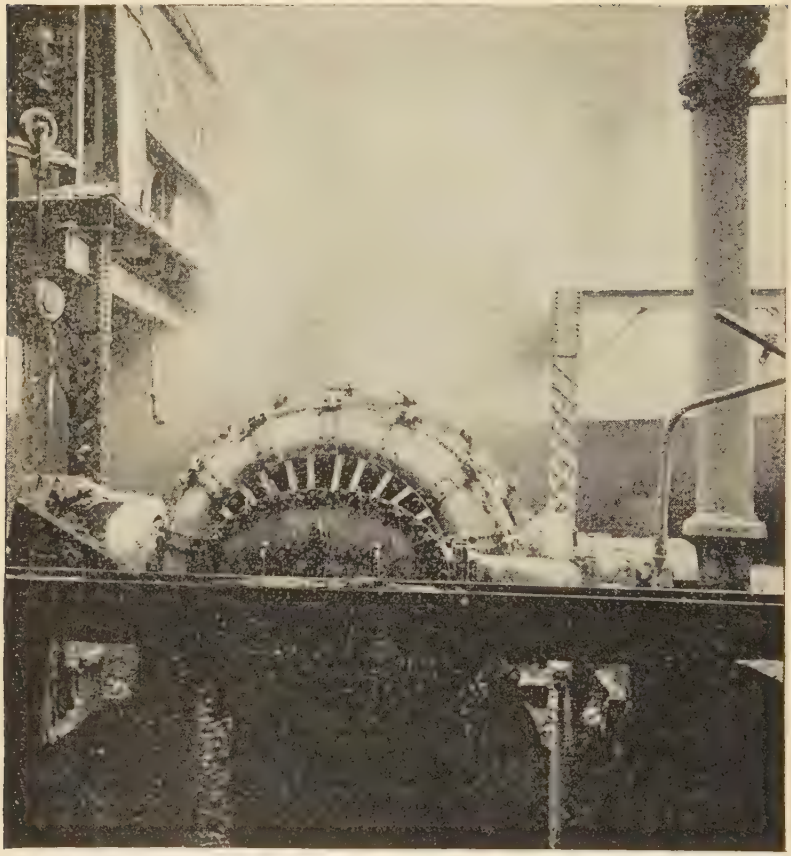


FIG. 74. View of Concentric Converter Turned Down to Receive the Charge of Hot Metal. View from teeming platform. Note the wind box and connections.

The Blow: Immediately after the vessel has received the charge of molten metal, the blast, under a pressure sufficient to prevent the metal from flowing into the tuyeres and also force the air through the liquid, is turned on, and the vessel is racked to the vertical position. With this act the air of the blast is forced to pass up through the molten mass, and chemical action between the oxygen of the air and the various ingredients of the metal immediately begins. This oxidation takes place in successive stages, each of which, provided the blow is a normal one, produces its own peculiar effect in the metal and upon the kind of matter ejected from the mouth of the vessel. Their order, therefore, may be followed by the naked eye or through colored glasses. As the vessel is righted a shower of sparks is emitted from its mouth. Then a stream of dense brown fumes pours forth, to be succeeded shortly by a dull red, short, pointed flame

that protrudes from the mouth of the vessel. This action occupies but five or six minutes, when this flame is gradually replaced by a short luminous one that plays about the mouth. This flame soon begins to increase, both in length and luminosity, until it has reached a maximum length of thirty feet or more, which it maintains steadily for about eight minutes. During this period, known as the **boil**, a dull roaring coming from the vessel may be heard. This noise is caused by the violent agitation of the bath by the blast and the rapid generation of carbon monoxide gas within it. Just before the end of the blow, the flame begins to drop, or "die," that is, it suddenly becomes less luminous, giving an effect similar to that to be expected if a smoked glass or a cloud were placed between it and the eye; and if it is being

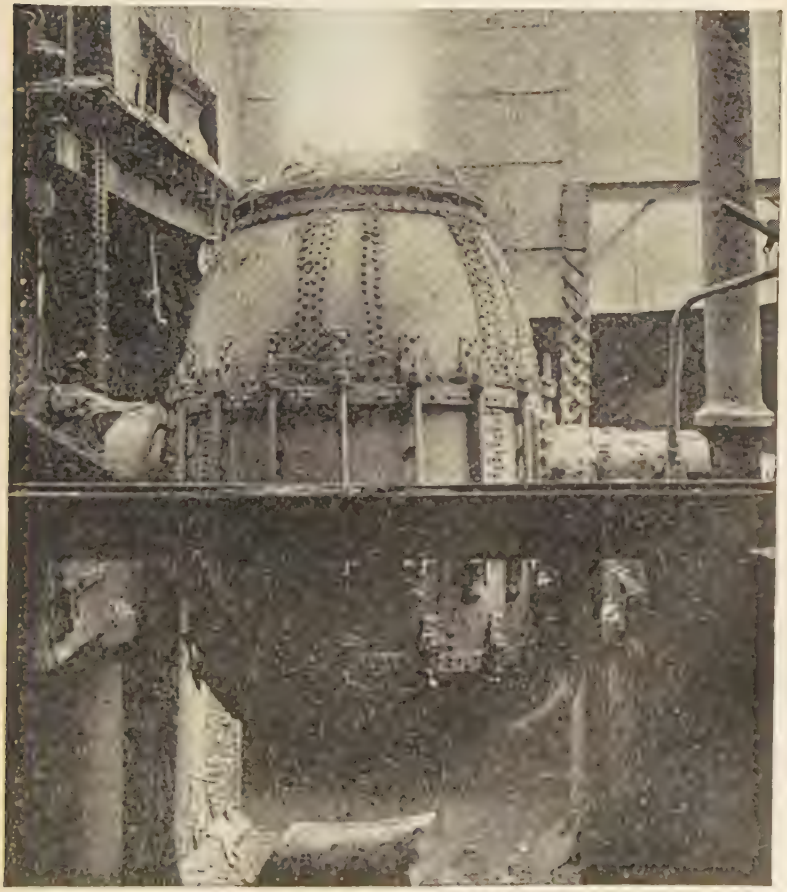


FIG. 75. View of Converter Shown in Fig. 74, with the Blow near the Beginning of the Boil.

observed through blue glasses, purple streaks are visible in it. If the blow should be continued, this flame would disappear entirely, but the vessel is always turned down before this point is reached. Thus, the entire time required to convert fifteen to eighteen tons of pig iron into steel is only about fifteen minutes.

Controlling the Blow: The appearance of the flame just described serves as an index to the change going on in the vessel, and so is very important to the blower, upon whom rests the responsibility for the proper operation of the vessel. He is also held accountable for the quality of the steel he produces. He has an assistant who turns the vessel for charging and pouring and operates the ladle crane, but the control of the process is in the hands of the blower himself. He must decide the best proportions of hot metal and scrap to use, regulate the temperature, determine the time for turning down and over-see the recarburizing of the blown metal. As to the kind of recarburizer and the amount to use per ton of steel, he receives instructions from his superintendent's office. Factors that enter into the making up of the charge have already been explained. The importance of a high temperature was also alluded to as necessary to keep the bath molten. In this connection it remains to be pointed out that temperature is an important factor in controlling the blow, and so exerts an influence on the quality of the product. As it is impossible to regulate the charge so as to meet all the variations in the conditions, other means of regulating the temperature must be resorted to during the blow itself. To raise the temperature after a blow is in progress, the vessel may be turned so as to expose a few tuyeres above the metal. The combustion of the carbon monoxide gas over the bath generates heat, which raises the temperature of the vessel and consequently of the metal also. This method wastes some metal, as iron is excessively oxidized. Ferro-silicon is also used for this purpose, the oxidation of the silicon being the source of heat in this case. Either method is expensive and should be avoided. With rapid working, and with iron of proper grade, cold heats are the exception, occurring mainly on new linings or in the first blow on a new bottom. To lower the temperature is a much easier matter. The vessel may be tilted and allowed to cool by radiation, or cold metal in the form of steel scrap may be added, if the heat is not too far advanced. A more convenient method is that of introducing steam with the blast, and as it is very convenient, it is often employed. The water coming in contact with the highly heated metal is decomposed according to the following reaction: $H_2O+Fe=FeO+H_2$. Steam thus introduced is not very efficient because the oxidation due to air is not retarded and very little, if any, heat can be absorbed. However, less heat is generated in oxidizing iron with water than with air, besides, steam is easily controlled, is always at hand, and can be introduced in varying amounts without delay to the blow or turning the vessel. The blower will, then, keep close watch on the flame, and introduce steam during the blow as often as required to hold the temperature at the

proper level. The speed of the blow, and, indirectly, the temperature, may be controlled to a limited extent, also, by varying the blast pressure. In this connection it should be stated that there are so many variables connected with the operations that no uniform method can be established. Even with metal of uniform composition and other conditions apparently alike, two consecutive heats made to the same specification will seldom require the same manipulation. Thus, the success of the entire operation depends upon the judgment of the blower.

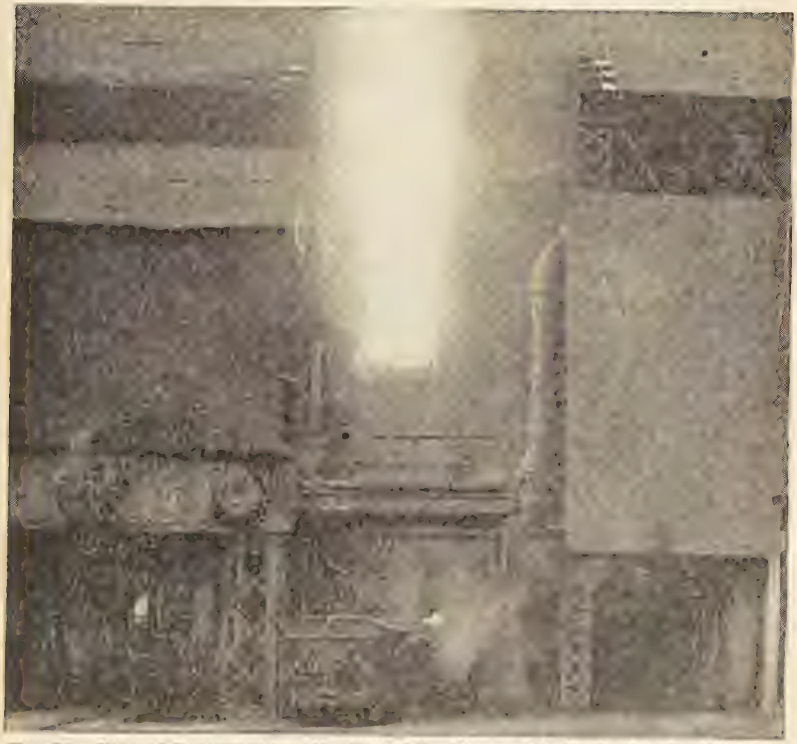


FIG. 76. View of Converter near the End of the Blow, while the Carbon is still being eliminated.

The End of the Blow: Owing to the rapidity of the reactions and other peculiar conditions, the composition of the steel cannot be well regulated by stopping the blow at an intermediate point. While it is possible to blow a heat to approximately any carbon content desired, a much more uniform product is obtained by blowing to the drop of the flame and adding the requisite carbon and manganese in the form of hot ferro-manganese or molten spiegel. This is the practice at Edgar Thomson. At these works, if the blow is stopped at the first indication of the drop of the flame, it is said to be turned down young; if continued till the drop is pronounced, the

blow is full. In either case the silicon will have been completely eliminated, while only small amounts of manganese and carbon will remain. The residual manganese may be as high as .06 or .08 per cent., depending upon the extent of the blow and the percentage in the pig iron. If the blow is turned down young, .08 per cent. to .10 per cent. carbon will remain, while in a full blow this amount is decreased to .03 or .04 per cent. The percentage of phosphorus and sulphur is slightly higher than in the original pig iron, owing to a loss in weight due to oxidation and elimination of the silicon, carbon, manganese and part of the iron, and also to the ejection of metallic iron from the vessel. The total loss will amount to something between 8 per cent. and 10 per cent. of the charge, nearly half of which is oxide of iron and manganese which can be recovered, in part, by using the slags in the blast furnace.

SECTION VI.

FINISHING OPERATIONS—CONVERTING THE PURIFIED METAL INTO STEEL.

Deoxidation and Recarburization must always immediately follow the blow. At Edgar Thomson this is done in the ladle as the metal is being poured, though at certain other plants some of the additions are made in the vessel. In general the objects sought are: 1st., control of the carbon content; 2d., deoxidation of the steel; and 3d., introduction of elements, such as manganese, to improve the quality of the steel. The following table shows the difference in the analysis of steel before and after recarburizing, and partly illustrates the many grades produced.

Table 36. Showing Chemical Relation of Purified Metal to Different Grades of Steel.

Kind of Steel	Per Cent. Carbon	Per Cent. Manganese	Per Cent. Sulphur	Per Cent. Phosphorus
As Blown..	.03 to .10	Trace to .06	.03 to .06	.08 to .100
Skelp.....	Not over .08	.30 to .40	Not over .06	Not over .100
Sheet Bar..	" " .10	.30 to .50	" " .06	" " .100
Screw Steel.	" " .08	.60 to .80	Not under .085	" " .100
Special Billet Steel	.25 to .30	.40 to .50	Not over .085	" " .100
Light Splice Bar.....	.08 to .10	.35 to .60	" " .06	" " .100
Rail Steel..	.30 to .50	.70 to 1.10	" " .05	" " .100

Needless to say, the different grades of steel require different methods of recarburizing to meet the requirements, which fact calls for different recarburizers. The various recarburizers and deoxidizers most commonly employed are ferro manganese, spiegel, anthracite coal, ferro-silicon, and pig iron, analyses of representative samples of which are given in the subjoined table.

Table 37. Analyses of Representative Samples of Deoxidizers and Recarburizers.

	Per Cent. Iron	Per Cent. Carbon	Per Cent. Manganese	Per Cent. Sulphur	Per Cent. Phosphorus	Per Cent. Silicon	Per Cent. Ash
Ferro Manganese..	11.95	6.50	80.40	Trace	.160	1.00	....
Spiegel.....	73 20	5.00	20.40	"	.100	1.10	....
Ferro-Silicon.....	86.70	2.00	.50	.050	.080	10.60	....
Pig Iron.....	93.05	4.50	.67	.047	.088	1.67	....
Anthracite Coal...	.....	85.50*	.....	....	....	.....	4.50

*Fixed carbon only.

Loss of Recarburizer and Deoxidizer: In adding the recarburizers, a loss always takes place, for which an allowance must be made. The amount of this loss is fairly uniform under similar conditions, and is determined by experience. In the case of manganese it amounts to about 20 per cent. of the manganese added for full blown heats, in which the per cent. of manganese does not exceed .60. The loss is somewhat less, not over 15 per cent., if the blow is stopped young. The loss varies, also, with the amount of manganese added, increasing rapidly as the per cent. in the steel is raised above .60. Similar data is required in using ferro-silicon and anthracite coal, the loss of carbon in using the latter being about 50 per cent. of the total amount added.

Examples of Recarburizing: Some simple examples of recarburizing will illustrate the methods employed. 1. Suppose it is required to produce a soft steel, such as the skelp shown in the table above. The metal will be given a full blow to reduce the carbon content to about .04 per cent., and **hot** ferro-manganese will be added in sufficient quantity to raise the per cent. of this element to .40. A simple calculation, if proper allowance is made for both residual manganese and manganese lost, will show that this amount of ferro will raise the per cent. of carbon to .08. 2. In the case of a medium soft steel, say .20 per cent. to .25 per cent. C., .40 per cent. to .50 per cent. Mn., the recarburization after a full blow may be made with molten spiegel mixture containing about 12 per cent. Mn. and 5 per cent. C., or, as it is difficult to handle and weigh small amounts of molten metal, coal and ferro-manganese are more often used. In the latter case, the blow may be turned down young. 3. In the case of a rail heat the blow is turned down young, and recarburized with molten spiegel mixture. Molten pig iron and ferro-manganese could also be used, but this is not the practice at the Edgar Thomson Bessemer plant. At this plant the cupola charge for the spiegel mixture used to recarburize rail heats consists of spiegel, ferro-silicon, and pig iron, in proportion to produce a mixture containing 12 per cent. Mn., 4.50 per cent. C., and 1.50 per cent. Si. For determining the quantity of deoxidizer and recarburizer to add,

the blower is provided with a set of factors, one for each grade of steel produced, the numerical values of which are fixed by experience. Thus, for sheet bar the factor giving the amount of 80-per cent. ferro-manganese to add, is .0045, but for skelp it is .0055, because this steel is blown very full. Similarly, factors for finishing rail steel with spiegel are given. To find the amount of recarburizer to add, the weight of molten pig iron blown is multiplied by the proper factor for each grade of steel produced.

Ladle Reaction: The addition of the recarburizer is usually followed by a violent boiling of the metal in the ladle, causing much slag to be thrown out over the sides. This is often referred to as the spiegel reaction or ladle reaction. With the addition of the recarburizer, precautions will be taken to mix it thoroughly with the metal. At Edgar Thomson this mixing is accomplished in the case of rail heats by using molten spiegel and pouring it into the ladle with the metal from the vessel, and in the case of soft steels by poling the metal in the ladle.

Teeming: The history of the heat may now be resumed Soon after the recarburizer has been added, the pouring of the metal will have been completed. The converter is then inverted, and the slag which did not flow out with the metal is dumped upon a small flat car beneath the vessel, which is then ready for the next charge. While this is going on, the steel has become quieter in the ladle and has been raised to the proper level by the steel crane, which then transfers it to the teeming table in front of the pouring platform. Here the teeming hole in the bottom of the ladle is opened by removing the small plate and digging out the sand, when the metal may be allowed to flow at will by raising and lowering the stopper lever. The metal is now teemed, consecutively, into four ingot moulds, which have been prepared as previously described. As each mould is filled to the mark, the next is moved under the nozzle by means of the "dog," hydraulically operated and provided for the purpose. During the teeming of each ingot of soft or medium soft steel, small pieces, about four ounces in all, of aluminum may be added, as the judgment of the teemer directs, to assist in further deoxidizing the steel. This metal will always be added if the steel is very wild, which condition is often found in soft steel made by this process. After all the steel has been teemed into the moulds, the little train is pushed along the track to the end of the teeming platform, where the ingots are allowed to cool. If the ingots show a tendency to grow in the moulds, the tops may be sprayed with water, and heavy caps of cold iron will be placed on them. This treatment is intended to chill the top and stop the growing, which invariably increases the number and size of the blow holes and pipe in the top of the ingot. Growing is peculiar to soft steels; rail heats seldom exhibit this tendency. When the ingots have cooled sufficiently to form a thick, strong shell on the outside, they are taken to the stripper, where the moulds are at once removed. This done, they are ready for the soaking pits, which are more properly treated under rolling mills.

FIG. 77.—Teeming the Steel into Ingot Moulds. The operator in the right foreground is pouring the sample for chemical analysis into the test mould.

Sampling the Steel for Chemical Analyses: A sample for chemical analysis is taken during the teeming of each heat. This matter is of much importance, and has received the attention it deserves. The sample is obtained when half of the ladle of steel has been teemed by holding a large steel spoon beneath the nozzle and allowing a small stream of the metal to flow therein until the spoon is full. This metal is then poured from the spoon into a specially constructed mould where it is allowed to cool or set, after which it is stamped with the heat number and is then taken to the chemical laboratory for analysis. Everything has been done to insure this sample is truly representative of the whole heat, which is seldom true of samples taken in other ways.

SECTION VII.

CHEMISTRY OF THE PROCESS.

The Order of Elimination of the Elements: As previously indicated, the heat required for the process is generated by the oxidation of the iron and the metalloids, silicon, manganese, and carbon. An examination of the blow will show that, during the first period, the oxygen of the blast attacks first the iron, then, both directly and indirectly, as will be explained shortly, the silicon and manganese, producing exothermic reactions which rapidly increase the temperature of the bath. The converter gases during this period are mainly nitrogen with some carbon dioxide and traces of oxygen and hydrogen. These reactions produce no flame, since the products of the oxidation are not combustible, but with the rise in temperature, carbon begins to be oxidized to carbon monoxide, which will burn at the mouth of the vessel to carbon dioxide and produce a flame outside the vessel. So, the heat generated by combustion of the CO to CO_2 is wasted. The rapid generation of CO in the metal produces the "boil," and the increasing speeds at which the formation of this gas takes place causes the flame to grow to a maximum size and finally subside with the elimination of the carbon. The escaping gases during this period consist mainly of nitrogen and carbon-monoxide with small percentages of carbon dioxide and traces of hydrogen. Thus, at no time during the blow, except for a short period at the beginning, does any but traces of the oxygen of the air escape from the bath uncombined, though the layer of metal is but some twenty inches thick, and the volume of the blast is more than 6000 cubic feet per minute. This fact is not surprising, if it is remembered that the temperature of the bath from the first is much above the kindling temperature for any element in the bath, and that the blast is delivered by the tuyeres almost in the form of a spray. Under these conditions, the combination of these elements with oxygen must be almost instantaneous, resulting in the consumption of all the oxygen at the mouth of the tuyere. Concerning the brownish fumes ejected by the converter, especially at the beginning

of a blow, various suppositions have been advanced to account for them. It has been suggested that they may be volatile compounds of iron and manganese with carbon, which, upon coming in contact with the air at the mouth of the vessel, are immediately oxidized, the metallic oxides producing the brown color. Analysis of deposits made by this fume have been made, and they are found to be composed roughly of one part ferrous oxide, two parts silica and three parts manganese oxide. Manganese is volatile at a comparatively low temperature, which fact may account for a part of the fume, but with respect to iron and silicon or silica, the most plausible explanation is that they are carried out mechanically in a finely divided state by the blast.

The Laws and Conditions Governing the Reactions in the Converter: A review of the laws of chemical action and of the conditions of the blow will render an explanation of the changes that take place to bring about the results enumerated above very easily understood. If reference be made to the laws controlling chemical action in Chapter I., it will be found that, under normal conditions of blowing metal, only two are applicable to the matter under consideration. One of these, the law of mass action, states, in effect, that the rate or speed of a chemical reaction may be increased by increasing the active masses, or amounts, of the reacting substances; and the other law says that when chemical reactions take place without the aid of heat supplied from an external source, those substances which have the greatest heats of formation, that is, those that give off the most energy, will tend to form. As to the conditions, these can be very briefly and simply stated. They are, that at the beginning of the blow the bath represents a solution of approximately 4 parts carbon, 1.5 parts silicon, 1 part manganese, .1 part phosphorus and .05 parts sulphur in 93.35 parts iron at a temperature that is several degrees, say 100° C, above the fusion point of the mixture; but this temperature is rapidly raised during the first part of the blow. The phosphorus and sulphur are not affected, so they need not be considered, but the elimination of the other impurities presents an interesting study. As to the question of whether these elements are all dissolved in the liquid metal as elements or as compounds that has not yet been decided. But, for the sake of simplicity, we will consider them, in the following discussion, as being in a state of atomic dispersion.

Reactions of the First Period: Chemical knowledge does not tolerate the idea that these impurities are oxidized by the action of oxygen directly, but indicates that the reactions occurring at the beginning of the blow are governed by the law of mass action. According to this law, iron, by far the most abundant element present, is first oxidized almost to the entire exclusion of the other three elements. This reaction, which liberates a large amount of heat, is represented thus:

$$(1)\ 2\ Fe + O_2 = 2\ FeO\ (+131400\ cal.)$$
$$2\ (65700\ cal.)$$

With the oxidation of the iron to FeO, this oxide, being miscible with the metal, is distributed throughout the bath, and the oxidation of the silicon and manganese takes place in the order of the heats of formation of their oxides, as shown in the following reactions:

(2) $2\,FeO + Si = SiO_2 + 2Fe$ (+64600 cal.)
Heats of formation:—2(65700 cal.)+(196000 cal.)

(3) $FeO + Mn = MnO + Fe$ (+25200 cal.)
Heats of formation:—65700 cal. +90900 cal.

With the oxidation of silicon and manganese, a slag is immediately formed by the combination of silica with the excess FeO and the MnO according to the following:

(4) $FeO + SiO_2 = FeO{\cdot}SiO_2$ (+9300 cal.)
Heats of formation:—65700 cal.—196000 cal. +271000 cal.

(5) $MnO + SiO_2 = MnO{\cdot}SiO_2$ (+5400 cal.)
Heats of formation:—90900 cal.—196000 cal. +292300 cal.

In comparing the ratio of acids to bases as determined by actual analysis with ratios calculated from formulas, evidence is obtained that the slag is made up, in part at least, of trisilicates, in which case these reactions would be represented thus:

(4 A) $2\,FeO + 3\,SiO_2 = (FeO)_2{\cdot}(SiO_2)_3$
(5 A) $2\,MnO + 3\,SiO_2 = (MnO)_2{\cdot}(SiO_2)_3$

This slag, itself a solution of the two silicates thus formed, will dissolve some of the FeO, and being mixed with metal by the violent agitation of the bath, will also help to oxidize the impurities. Reactions (1) and (4) also account for the rapid wearing away of the bottom. This period is then preeminently one of slag formation. Some carbon, especially toward the end of the period, however, may be oxidized directly to CO and then to CO_2 by the FeO, thus:

(6) $2C + O_2 = 2\,CO$ +(58320 cal.)
2(29160) cal.

(7) $FeO + CO = Fe + CO_2$ (+2340 cal.)
—65700 cal.—29160 cal.+97200 cal.

These reactions account for the presence of both CO_2 and CO in converter gases during the first part of the blow. At the beginning of the blow, CO is subject to reduction by both silicon and manganese, especially if the iron contains a high per cent. of these elements.

(8) $2\,CO + Si = SiO_2 + 2C$ (+137680 cal.)
—2(29160) cal.+196000 cal.

(9) $CO + Mn = MnO + C$ (+61740 cal.)
—29160 cal.+ 90900 cal.

Reactions of Second Period: With the elimination of silicon and manganese, reaction (8) and (9) cannot take place. Furthermore, the rise in temperature brings about reaction (10) or (10A).

$$\underset{-65700\text{ cal.}}{FeO} + C = \underset{+29160\text{ cal.}}{Fe + CO} \quad (-36540\text{ cal.}),$$

$$\underset{-65700\text{ cal.}}{FeO} + \underset{-8460\text{ cal.}}{Fe_3C} = 4Fe + \underset{+29160\text{ cal.}}{CO} \quad (-45000\text{ cal.})$$

These reactions, in conjunction with reaction (6), rapidly burn out the remaining carbon. According to the law involving heats of formation, these reactions should not take place, and it becomes necessary to explain certain apparent exceptions. At ordinary temperatures the law has no exceptions, but at elevated temperatures it holds true through certain ranges of temperature only, so that, as the temperature in any particular case is raised, a point, which may be called the critical temperature, is reached, where the energy supplied from the external source overbalances that absorbed by the reaction. The law then becomes reversed, and the reaction proceeds in a direction that will absorb the excess heat. This fact suggests the possibility that with hot iron, that is, iron high in silicon, which is also initially at a very high temperature, it might be possible to eliminate the carbon before the silicon and manganese could be oxidized, and the testimony of the older and more experienced operators of converters is to the effect that just such a result as this has often occurred when the conditions noted were present. Furthermore, in the elimination of the carbon, the law of mass action here becomes prominent again, for with the elimination of the silicon and manganese the active mass of the ferrous oxide rapidly increases until a second equilibrium is established, this time with carbon. The reaction is also probably influenced by the volatility of the carbon monoxide, one of the products of the reaction. Comparatively little heat is available in the bath during this period. The net heat generated is the difference between the heat of formation of FeO (65700 cal.) and that absorbed in reaction (10) (36540 cal.), or 29160 cal., which is the heat of formation for CO. The carbon reaction occurs concurrently with the phenomenon commonly spoken of as the boil. There is, during this period, very little, if any, iron oxidized above that required to eliminate the carbon, so each volume or molecule of oxygen in the blast will produce two volumes or molecules of CO. The converter gases, therefore, show a high content of CO, very little CO_2 and a marked decrease in N_2. The phosphorus and sulphur suffer no oxidation from the action of FeO until all but traces of carbon is eliminated, and then only in the presence and under the influence of a strong base, such as lime. If the loss in weight in the bath be taken as 10 per cent., then steel made from iron containing .045 per cent. sulphur and .089 per cent. phosphorus would show approximately .050 per cent. sulphur and .100 per cent. phosphorus immediately after the blow. These percentages are affected but slightly by the recarburizer.

Chemistry of Recarburizing and Deoxidizing: The importance of this part of the operation is more fully appreciated when it is recalled that the Bessemer process was made a commercial success only through deoxidizing with manganese. This element, then, plays a very vital part, the effect in the product most evident being the prevention of that combination of hot and cold shortness commonly spoken of as rottenness. It is due to the presence in the metal of iron oxide, FeO, which is dissolved by molten iron. This oxide is reduced by metallic manganese, thus: (a) $FeO+Mn=MnO+Fe$. As MnO is not soluble in iron to any appreciable extent, reaction (a) will result in ridding the steel of all but traces of metallic oxide. Carbon may act as a deoxidizer, according to some authorities, as shown by reaction (b).

(b) $FeO+C=Fe+CO$.

However, the evolution of CO gas that produces the violent boiling of the metal in the ladle, which boiling often continues also in the ingot mould after the metal has been teemed, is probably caused by CO and other gases passing out of solution in the metal as the latter cools. Small amounts of these gases retained by the steel produce the blow holes previously alluded to. It is to be noted, also, that manganese offsets the evil effects of sulphur as will be explained in a later chapter. The silicon as well as the carbon and manganese in the ferro or spiegel and pig iron will also serve as a deoxidizing agent. Besides, silicon, by attacking CO, prevents the formation of blow holes. For the greatest effectiveness a considerable excess of silicon and manganese over that required by their respective reactions should be used. This is one of the reasons why the manganese in steel will range from .30 to 1.00 per cent. Additional losses of the manganese in the recarburizer are likely to occur by reacting with the silicate of iron oxide, thus:

(c) $FeO\cdot SiO_2+Mn=MnO\cdot SiO_2+Fe$.

A study of Bessemer slags shows that a slight decrease of iron oxide without a corresponding increase of MnO takes place on recarburizing. This circumstance is usually explained by assuming that one of the following reactions takes place:

(d) $FeO+C=Fe+CO$ or

(e) $2FeOSiO_2+CO=FeO\cdot(SiO_2)_2+CO_2+Fe$.

As was pointed out under the head of teeming, other deoxidizing agents may be added to the ingot as the metal is being teemed. The one most commonly employed is aluminum. This element is one of the most powerful deoxidizers known. Upon being heated to a sufficiently high temperature it will react violently with all the metallic oxides, and also many others.

(f) $3FeO+2Al=Al_2O_3+3Fe$.

Various alloys are beginning to be used for this purpose, also. One of the best is known as "A. M. S." metal; it is an alloy of aluminum, manganese and silicon, and is said to be very efficient for this purpose.

CHAPTER X.

THE OPEN HEARTH PROCESSES.

SECTION I.

SOME GENERAL FEATURES OF THE SIEMENS PROCESS.

Early History of the Process: The ever increasing demand for steel, which even the phenomenal success of Bessemer was not able to meet entirely, soon led many other inventors into the same field. But the only process which was destined to become a rival of the Bessemer was developed through the invention of the regenerative principle by that prolific inventor, William Siemens. In this connection it may be of interest to note that Siemens first developed and employed this principle in the construction of steam engines. But while several of these engines were built and put into use, they were finally abandoned because of the severe wear on the heating chambers caused by the high temperature attainable. But it was shown that a great saving of fuel and very high temperatures could be obtained by the use of the principle, and at the suggestion of his brother, Frederick, Siemens then turned his attention to the application of the principle for producing high temperatures in furnaces. The first experimental furnace was built in 1858, when it was developed that, with large furnaces especially, many difficulties were to be overcome, if the full efficiency which the use of the principle promised was to be obtained. After two years or more of experimentation, Siemens fell upon the plan of gasifying the fuel prior to burning it in the furnace, when he found that most of his difficulties had been overcome. The first furnace burning gaseous fuel, patented in 1861, was used for making glass. Here, the great advantages of the furnace in economy and regularity of working were fully proven, and it was not long until it was adopted in other industries, also. Some of these early uses of the furnace were for zinc distillation, for puddling, for reheating iron and steel, and for melting crucible steel. Siemens next turned his attention to the manufacture of steel in his furnace, and, though many trials were made at many different works, he met with only indifferent success. Finally, like Bessemer, he found it necessary to erect a steel works of his own in which the success of the process could be demonstrated. These works were located at Birmingham, England, and were at first employed in a remelting process by which steel of the best quality was obtained from such scrap as old iron rails, plates, etc. In the meantime, Siemens was busy developing an idea of decarbonizing pig iron for making steel by means of iron ore, and by the year 1868 he had proved that this process could be successfully employed. Siemens next turned his attention to

evolving a method whereby steel could be produced directly from the ore, thus dispensing with the blast furnace. In this feat he actually succeeded, but the cost of production was many times that of producing steel from pig iron. Nevertheless, he continued his experiments until his untimely death in 1883 put an end to his endeavors. He died firmly believing that his direct process would eventually supplant all conversion methods. Subsequent endeavors have shown this idea is wrong, and that his pig and ore process is the most practicable and economical.

Principles of Siemens Pig and Ore Process: Briefly, the method of Siemens was as follows: He used a rectangular covered furnace to contain the charge of pig iron or pig iron and scrap, and provided most of the heat for the chemical reactions by passing burning gas over the top of the materials. The gas, with a quantity of air more than sufficient to burn it, was introduced through ports at each end of the furnace, alternately at one end and the other. The gaseous products of combustion passed out of the port, temporarily not used for entrance of gas, into chambers partly filled with checker brick, which absorbed some of their sensible heat, and from these chambers out through a stack. After a short time, the gas and air were shut off at the one end and introduced through the heated checker chambers at the opposite end, absorbing some of the heat stored in the bricks. These gases then entered the furnace with a high sensible heat and gave a higher temperature in combustion than could be obtained without preheating. In about twenty minutes, the course of the gas and air was reversed, so that they entered through the port first used; and a series of such reversals, occurring every fifteen to twenty minutes, was continued until the oxidation had reached the desired point. The elements in the iron attacked by the oxygen of the air and of the iron ore fed in were carbon, silicon and manganese, all three of which could be reduced to as low a limit as in the Bessemer process. Thus, as in all the other processes for purifying pig iron, the basic principle of Siemens' process was that of oxidation. But in other respects it was unlike any other process. True, it resembled the puddling process in both the method and the agencies employed, but the high temperature attainable in his furnace permitted him to secure in the liquid state a perfectly malleable metal which could be cast into ingots and be free of slag. In this respect the same result was produced as in the Bessemer process, but by a different method and through different agencies, both of which imparted to it many advantages over the older pneumatic process.

Advantages of the Process: These advantages may be briefly summed up as follows: 1. By the use of ore as an oxidizing agent and by the external application of heat, the temperature of the bath is made independent of the purifying reactions, and the elimination of the impurities can be made to take place gradually, so that both the temperature and the composition of the bath are under much better control than in the

Bessemer process. 2. For the same reasons, a greater variety of raw materials can be used and a greater variety of products can be produced by this than by the Bessemer process. 3. A very important advantage is due to the increased output of finished steel from the same amount of pig iron, which means that fewer blast furnaces are required to produce a given tonnage of steel. 4. Finally, with the development of the basic process, the greatest advantage of the Siemens over the Bessemer was revealed through the elimination of phosphorus. Comparing the basic open hearth with the Thomas-Gilchrist process it is to be noted that, due to the different temperature conditions, phosphorus is eliminated in the former before the carbon, whereas it is not oxidized in the latter process until after the carbon, in what is known as the after-blow. Hence, while the basic Bessemer process requires a pig iron with a phosphorus content of 2.00 per cent. or more in order to maintain the temperature high enough for the after-blow, the basic open hearth permits the use of iron of any phosphorus content. In the United States this fact is of the greatest importance, since, for reasons already explained, it makes available immense ore deposits which could not otherwise be utilized. For this reason the basic open hearth process has become the leading method in this country.

Mechanical Changes and Improvements in Siemens Process: As would be expected, many variations of the process, both mechanical and metallurgical, have been worked out since Siemens first put his method into operation. Along mechanical lines various improvements in the design, the size and the arrangement of the parts of the furnace have been made. Originally, the furnace had a capacity of only four or five tons, but now the size ranges from 40 to 100 tons capacity, and in new plants the capacity will seldom be less than 75 tons. But the greatest departure from Siemens' original plan was made by the invention of the tilting or rolling furnace. These furnaces are of two types, and are known as the Campbell and the Wellman furnaces, respectively. In each case the furnace is built of brick, which are held firmly in place by a strong framework of steel, and is mounted upon rollers or rockers, thus permitting it to be tilted either forward or backward. In the Wellman type the hearth and ports are built solid, so that both move together; and as tilting the furnace breaks the connections with the regenerator flues, the furnace can be fired only when in an upright position. This fault is overcome in Campbell's invention, in which the hearth only is movable, and the center of rotation is coincident with the center line of the ports. By the use of water cooled castings, fairly tight joints are made between the hearth and the flues, so that the furnace may be tilted in either direction, forward or backward, without turning off the gas and air.

Metallurgical Improvements: The hearth of Siemens' furnace was of acid brick construction, and the bottom was made up of sand—essentially as in the **acid process** of today. Later on, in order to permit the charging

of limestone for the removal of phosphorus, the hearth was constructed with a lining of magnesite brick, which were covered with a layer of burned dolomite or magnesite to replace the sand of the acid furnace. These furnaces were, therefore, designated as **basic** furnaces. **The pig and scrap process** was originated by the Martin Brothers. By substituting scrap for the ore in Siemens' **pig and ore process** they found it was possible so to dilute the charge with steel scrap that little oxidation was necessary. Since the time of the Martins, these processes have undergone various modifications, chief of which are those known as the Talbot, the Campbell, the Bertrand-Thiel, and the Monell processes. By using a basic lined tilting furnace in which a large bath of the purified molten metal is always retained, Talbot succeeded in hastening the oxidation of the silicon, manganese, phosphorus and carbon to such an extent that the operation is made more nearly continuous, and the time between heats or tappings is greatly reduced. Campbell's tilting furnace permits him to apply the pig-and-ore process to molten metal, because, by tilting the furnace forward, the frothing of the bath, produced by the violent reactions, is prevented from throwing the slag through the doors as would be the case in a stationary furnace. By a combination process, he also aims to make acid steel from basic pig iron. In a basic lined furnace he eliminates the silicon, manganese, phosphorus and a little of the carbon, then pours this semi-purified metal into an acid furnace, where the remainder of the carbon is worked down as in the regular acid process. The Bertrand-Thiel process is applied to pig iron with a very high phosphorus content, and makes use of the two-period scheme of purification, also. In the first period, the furnace is tapped in order to separate the metal from the slag, which contains such a high percentage of phosphoric acid, P_2O_5, that it is valuable as a fertilizer. The metal is then poured either back into the same furnace or into another basic furnace for the final purification. In developing his process, Monell had the same objects in mind as Talbot, namely, the rapid conversion of basic iron into steel; but he wished to avoid the reservoir of molten metal, and make his process adaptable to the stationary furnace. He accomplished his object by first charging limestone and ore into a basic furnace, heating these until the batch became pasty, then adding molten pig iron, when the silicon, manganese, and phosphorus were rapidly oxidized and, with the lime, formed a slag that, as the carbon began to be oxidized, foamed up and ran from the furnace through slag notches provided for the purpose.

The Process for the Pittsburgh District: Most of the pig iron available in the Pittsburgh district contains a fairly high percentage of phosphorus, and the mills produce considerable scrap. Hence, the furnaces are practically all basic—the Carnegie Steel Company no longer operates any acid open hearth furnaces—and a combination of the pig-and-ore, pig-and-scrap, and Monell processes is employed. It has been briefly described as follows: Limestone is charged on a basic bottom, ore is charged on top of the stone, and scrap on top of this; if molten pig iron cannot be obtained

in sufficient quantity to complete the charge, some cold pig is charged with the scrap; and the entire mass is heated in the furnace for about two hours, or until the scrap is white hot and slightly fused. Molten pig iron is then added, when a lively reaction occurs, in which almost all of the silicon, manganese, phosphorus and part of the carbon are oxidized, the first three forming compounds that slag with the iron oxide, and join the iron and lime silicates that are already melted. About 80 per cent. of this slag is drawn off by the end of two or three hours more. The ore acts on the carbon for three or four hours longer, during which time, and continuing afterwards, the limestone is being decomposed by the heat, and its CO_2 is bubbling up through the bath and exposing part of the metal to the flame, thus oxidizing it and completing the purification started by the ore reaction. What is known as the lime action, or boil, lasts two or three hours longer; and then, if the charge was calculated correctly, the carbon content will be somewhat greater than that at which the metal is to be tapped. Ordinarily, of course, the carbon is too low or too high, in which cases more pig or more ore must be added. In about another hour the carbon content will have been reduced to the proper amount for tapping, which is usually about .10 per cent.

SECTION II.

EQUIPMENT FOR A MODERN BASIC OPEN HEARTH PLANT.

The Modern Plant: Besides the furnaces themselves, the modern open hearth plant requires considerable additional equipment. Thus, there must be provided ladles for containing molten metal; moulds for ingots; cranes and charging machines for handling materials; boxes for the solid materials; dinkeys or electric-engines for hauling the materials; a stripper for removing the moulds from the ingots; a great number of small articles, like shovels, wheel barrows, rabbles, etc.; and, finally, apparatus for preparing or controlling the fuel supply. In addition, the more modern plants will be provided with a mixer; spiegel-cupolas, if liquid recarburizers are used; and, in case the basic process is employed, a calcining plant. A brief description of the more essential items enumerated above is given herewith.

Calcining Plant: Basic open hearths require a great deal of freshly calcined dolomite for repairing the banks and bottoms. Therefore, if basic furnaces are used, this dolomite is usually roasted in cupolas at the plant. These furnaces are cylindrical in form, and each one is so placed that one base forms the bottom, the other the open top of the furnace. In the usual construction the cupola is made up of an outer shell of boiler plate, one-half inch thick, and a double refractory lining made of two courses

of brick, the inner one being of first quality and the outer one next to the shell of second quality fire brick On the floor of the furnace, there is a cone shaped casting which deflects the burnt dolomite, in its descent, toward the circumference, where it may pass out through openings provided for the purpose in the base of the cupola. For fuel, coke is employed, and it must be burned by an air blast. This blast is supplied at a pressure of five to six ounces. A bustle pipe distributes the air and is provided with about eight tuyeres, or connections, with the cupola. Built on the charging platform and extending about three feet above it, there is a seat upon which the charging bucket is deposited by a crane and from which its contents, through a bell and hopper arrangement in the bottom of the bucket, may be dropped into the cupola. Usually the ratio of materials in the charge is two buckets of dolomite to one bucket of coke. Thus, the fuel consumption is about 15 per cent. of the weight of dolomite calcined. The operation of

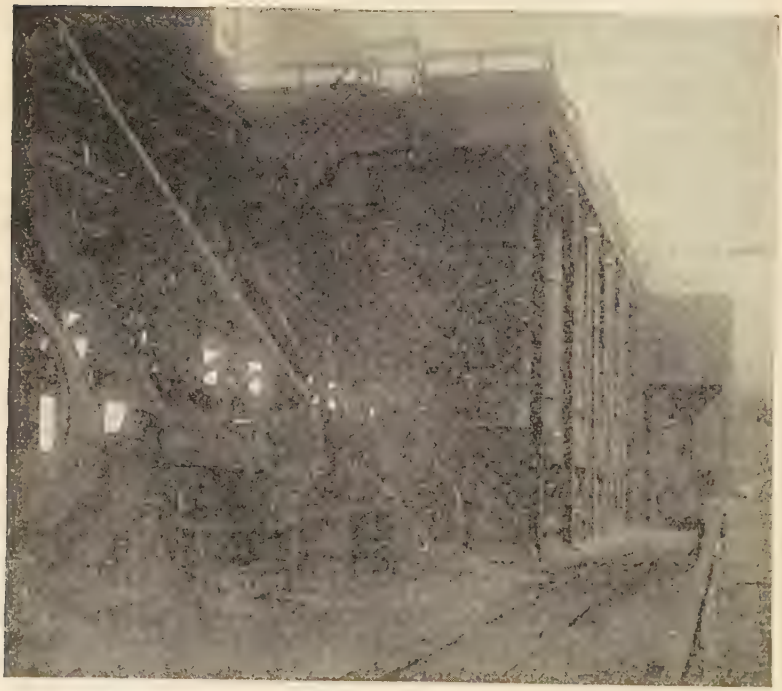


FIG. 78. View of Modern Calcining Plant, Showing Cupolas and Grinding Machines.

burning, in which the CO_2 is expelled from the stone, leaving calcium and magnesium oxides (CaO and MgO) in place of their carbonates ($CaCO_3$ and $MgCO_3$), requires from ten to twelve hours. The burning period is controlled by the rate at which this material is withdrawn. As fast as the dolomite is burned it is shoveled out at the bottom, crushed to pass a half-inch mesh, then conveyed to the loading bins, whence it is later taken as required to the open hearth.

Fuels: For fuels in open hearths, natural gas, coke oven gas, producer gas, pulverized coal, fuel oil and, sometimes, tar are used. The choice of fuel depends largely upon the location of the plant. Natural gas is, of course, preferable when it can be obtained, as it is of uniform composition, is easily controlled and imparts no sulphur to the bath, while coke oven gas, producer gas and pulverized coal are of varying composition and quality and may impart some sulphur to the bath. The great demand for petroleum products has made fuel oil too costly, while the supply of tar is so limited that it is not always available as an open hearth fuel. There remains, then, as the principle substitutes for natural gas, only pulverized coal, coke oven gas and producer gas, all of which have already been discussed in the chapter on fuels. In either case, coal of the best grade obtainable is desired, especially with respect to sulphur, as there is always danger of its being absorbed by the bath. In using coke oven gas from which the benzol has been removed, it is found necessary to mix some air with the gas previous to combustion or to burn with it some substance like tar, for example, in order to impart luminosity to the flame, as otherwise the poor visibility within the furnace makes it difficult for the melter to control the temperature. In the new plants of the Carnegie Steel Company, the producers are connected in sets of four—five in one or two cases—and each set serves two furnaces, the gas mains from the producers being arranged so that any one or all of the producers in a set may discharge into either one or both of the furnaces.

Fuel Consumption: It is a difficult matter to arrive at any conclusion as to the amount of heat required to produce a ton of steel. It is subject to a number of conditions such as kind of fuel used, condition of the furnace and checkers, continuity and rate of production, and the care and intelligence with which the furnace is operated. In actual practice the number of heat units per ton of steel produced is found to vary from 5,000,000 B. t. u. to 6,000,000 B. t. u. when natural gas is used, and from 6,000,000 B.t.u. to 8,500,000 B.t.u. when other fuels are employed. An inspection of the fuel records of several different plants and a consideration of averages for long periods of time, varying from six months to a year, indicate that the fuel consumption per gross ton of steel produced, to be considered good practice, should be about as follows: natural gas, 5,000 cubic feet; coke oven gas, 8,000 cubic feet with 16 gallons of tar; tar alone, 45 gallons; producer gas equivalent to 600 pounds of coal; and pulverized coal, 500 pounds.

Hot Metal Mixer: The advantages of the hot metal mixer have already been discussed in connection with the Bessemer process; and although the conditions in the open hearth plant, where large quantities of metal are needed at irregular and uncertain intervals of time, are exactly the reverse of those in a Bessemer plant, which requires small quantities of metal at short and comparatively regular intervals, these advantages are as applicable to the one case as to the other. In order that these advantages may be realized to the fullest, open hearth mixers should have a large capacity. One large mixer of 1000 or 1200 tons capacity is to be preferred to two of 500 tons capacity.

Spiegel Cupolas: In plants manufacturing large quantities of medium high carbon, high manganese steels, such as is used for railroad rails, for example, the use of spiegel for recarburizing may be advantageous, in which case cupolas for melting the spiegel mixtures are an important adjunct to the open hearth plant. In construction and operation, these cupolas are similar to those already described for the Bessemer plant. For collecting and weighing the different ingredients of the charge, a larry car equipped with a multiple beam scale is most convenient. In charging, the metallic parts of the burden, consisting usually of spiegel and pig iron, are charged into the cupola together, while the coke, with which is mixed enough limestone to flux its ash, is charged separately. The proportion of coke required in each round will vary somewhat, but in good practice it will seldom exceed seven per cent. of the weight of the metallic part of the charge. To secure greater uniformity and provide an ever-ready supply of molten recarburizer, the cupolas attached to the most modern plants are provided with a small mixer. By means of brick and clay lined runners the metal from the tap hole of each cupola is conducted directly into this mixer, from which definite amounts may be taken as desired. For weighing the recarburizing metal, a track scale, on which the transfer ladle may rest during the pouring, is placed on the track directly in front of the mixer. The manganese content of the molten recarburizer is varied to suit the requirements of the different grades of steel by varying the amount of pig iron with which the standard spiegel is diluted. Varying the proportion of pig iron to spiegel also changes the carbon content of the mixture slightly. With a given weight of standard spiegel, the more pig iron charged the lower the carbon content of the mixture will be, as can readily be seen by comparing the analyses of these materials.

The Steel Ladles: The ladle for receiving the steel is made of boiler plate and is lined with two courses of brick each 2½ inches thick. The first layer, next to the shell, is usually of fire brick, while the second layer is of white river brick. Both courses are laid on end in a mortar of fire clay, to which a little loam is sometimes added. The capacity of the vessel is dependent on the amount of steel to be handled in each heat, which in turn is fixed by the capacity of the open hearth. The opening at the bottom of the ladle is provided with a fireclay nozzle about two inches in diameter, which may

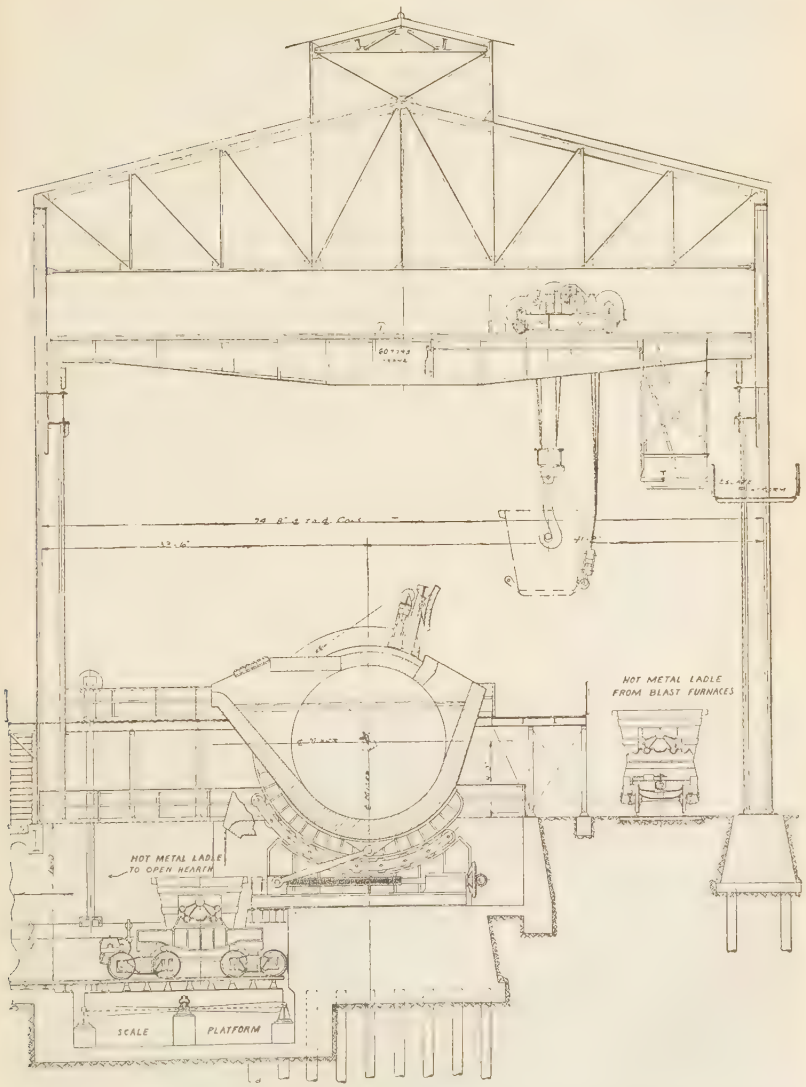


FIG. 79. Drawing Showing General Arrangement of a 1300-ton Mixer Plant. The mixer, which is shown in divided cross section, is cylindrical in form with the charging door at one end and the pouring spout at the other.

be closed by a stopper. The stopper is made of clay bonded graphite and is mounted on a rod, protected by fireclay sleeve brick, that reaches to the top of the ladle; there it is connected to a sliding bar on the outside that can be raised or lowered by a lever near the base. Both the stopper and the nozzle must be replaced after each heat. Great care is necessary both in placing the nozzle and in setting the stopper in the nozzle, for a bad fit results in a running stopper, which may cause a great waste of metal. To prevent the steel from chilling about the stopper, powdered coal is often thrown into the depression around the nozzle just before tapping a heat.

The Stripper: The action of this machine has already been described in connection with the Bessemer process. The ingots must all be sufficiently cooled before stripping, so that there will be no danger of breaking the solidified wall of metal. After being stripped, the ingots are then ready to be sent to the soaking pits previous to the rolling. To strip an ingot, it is only necessary, in the majority of cases, to place the jaws of the stripping machine under the lugs on the mould and apply the lifting force, when the mould will slip from the ingot and can then be raised to a sufficient height to transfer. It is only at times, usually due to a defective mould or to metal being splashed over the top edges from a running stopper, that the moulds are not slipped off easily, and then the plunger is rested on top of the ingot as the mould is drawn upward. When this treatment fails to loosen an ingot, it is sent to the mould yard where more time is available for extracting it and where it may be subjected to various treatments according to the means at hand and the cause of its sticking.

Fig. 80. View of Electric Stripper.

Moulds: After the ingots of each heat are stripped, the empty moulds are stored in the mould yard until they are sufficiently cool to be drawn back to the open hearth for another charge, and during the wait they are inspected and cleaned of adhering particles of steel that may remain about the top from splattering in pouring. Any damaged moulds that cannot be used are charged as cold iron, as they are cast from a good grade of Bessemer pig iron. Many types and sizes of moulds are used. Heavy moulds chill the surface of the steel quickly and hasten the solidification, which always proceeds from the wall of the mould toward the middle of the ingot. Since steel contracts on solidifying, there is a cavity left directly under the top surface of the ingot, as the metal in this location is the last to solidify. This cavity, called the **pipe,** is responsible for the production of a great deal of scrap in rolling the steel. There are numerous methods to reduce the size of the pipe and to keep it as near the top as possible, but it cannot be entirely eliminated. The principle of most of the devices is to keep the top of the ingot molten longer than the bottom, so that the molten steel on top will flow into the cavity as fast as it forms and thus lessen the extent of the pipe. The Gathman type of mould depends upon uneven thickness of mould wall to effect the same result. By having the mould thin at the top and thick at the bottom, the thin top has a less chilling effect on the molten steel at the top, which, therefore, is the last to solidify. A similar method consists in lining a removable top of the mould with brick or clay, thus preventing rapid conduction and radiation. Some try to keep the steel at the top of the ingot fluid by a coke, a charcoal or a gas fire. Many other more complicated devices have been invented, also, but their use involves much additional expense. Besides, piping is regarded by many as a necessary evil, and the safest way to avoid it is to allow a proper discard from the top of the ingot, which discard is cut off at the blooming mill shears. Ingots for some classes of work are bottom cast. By this method the metal is admitted to the mould through the stool, or bottom, by means of a runner which connects with the riser into which the steel is teemed. In case several moulds are poured from the same ladle, these are arranged in a circle about the riser. The method is costly, and, as avoidance of splashes on the sides of the mould is its only advantage, it is used mainly with steel for special purposes. Large ingots for forging are sometimes bottom cast in specially constructed hard sand moulds.

The Charging Machine: Of all the labor saving devices employed about the open hearth plant, none have brought a greater saving of money and time than the charging machine. Indeed, it may be looked upon as the most essential part of the equipment, for if the charging were done by hand, the time thus lost, especially in the case of the large furnaces, would be so great that this feature would appear as a serious drawback to the process. There are several types of these machines, but the ones most generally employed are of the low ground type. They consist of two main parts.

First, there is the bottom truck made up of a very strong steel frame-work and mounted on flanged wheels which travel on a very wide gage track laid in front of the furnace. Next, there is the charging carriage, which moves over a track, laid on the frame of the truck, at right angles to the direction of motion of the truck itself. On this carriage is mounted a kind of lever, the long arm of which extends toward the furnace and is known as the charging bar. The charging bar is hollow to provide space and bearings for the locking bar, about which it can be made to revolve, and is shaped on the end to fit into the socket of the charging box. The charging bar is thus capable of giving eight different primary motions, or any number of resultants of these motions. In operating the machine, the charging boxes rest on buggies running on a standard or narrow gage track between the machine and the furnace. First, the truck of the machine is moved so that the charging bar is directly opposite the charging box to be emptied, then the carriage is moved forward to bring into position the end of the charging bar, which is then dropped into the socket on the end of the charging box and locked in position by advancing the locking bar until its front end projects into a hole provided for the purpose in the socket of the box. Now, the machine is made to serve for a shifting engine, and, by moving the truck, the whole train of charging boxes may be moved along in front of the furnace, so that the box engaged is brought directly opposite the furnace door. The charging bar is then raised, carrying the box with it, and by a forward motion of the carriage the box is passed into the furnace, where, by rotating the charging bar, the box is turned upside down and its contents deposited. By reversing these motions the box is then placed upon the buggy again. The charger will pick up and empty a box in less than a minute. As the capacity of the box is more than one ton, for even the lightest materials of the charge, it is possible to charge even the very large furnaces in less than an hour. Charging machines are always electrically operated.

Charging Boxes: The charging boxes are made of cast steel or of five-eighth-inch boiler plate with cast steel ends. One end of the box is provided with a socket opening from the top, so that the T section on the end of the charging machine peel, or arm, may readily be inserted and withdrawn from it. The boxes have a capacity of sixteen cubic feet or more, and into them all solid material for the furnace charge is placed. For transporting the boxes from place to place about the works, buggies are provided. These buggies are of standard or narrow gage type, are made of cast iron and accommodate three to four boxes each.

Stock Yard: There is usually one stock yard to each plant. In it are kept the stores of limestone, ore, cold pig and, sometimes, scrap, from which materials the cold charges for the furnaces are made up. The ore and limestone are loaded into the boxes from chutes or by grab buckets, depending upon the manner of storing; the cold pig from railroad cars or from a stock pile by means of a magnet; while the scrap is brought from

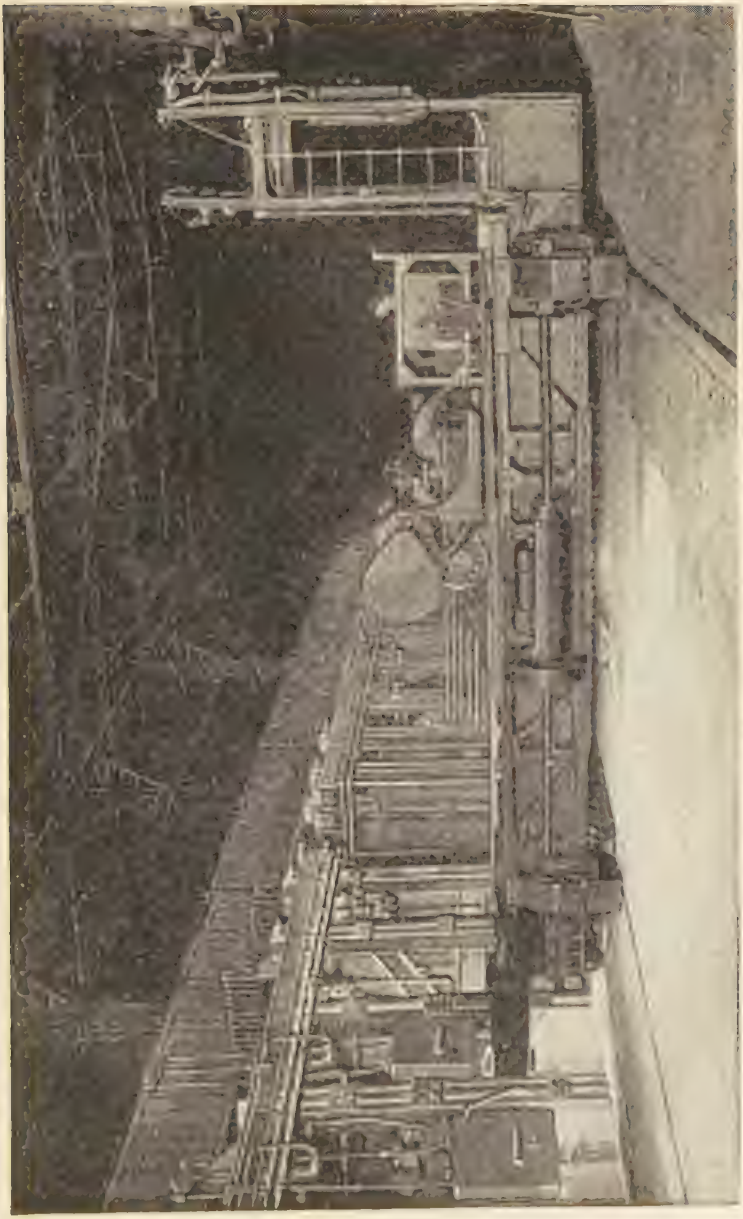


FIG 81 View of Open Hearth Charging Machine in Operation

the rolling mills ready loaded in the charging boxes, or if it is delivered in railroad cars, it is transferred to them by magnets. Soft ore is generally used to make up a charge on account of its lower cost, because there is no advantage in charging lump ore on the bottom, and it is not necessary to have as pure an ore as is the lump ore. After a charge is made up, the buggies are pushed over platform scales and weighed by the weighmaster, who records the weights in a stock book. The stock-yard men take into account the amount of pig iron to be used and, to a certain extent, the carbon contents of the scrap charged and add to the charge what ore they think will be necessary. Reports giving the weights of all materials are made out in triplicate, one of which is sent to the melter, so that after it reaches the furnace front the melter-foreman or his first helper may vary the ore charge to suit their plans or ideas.

Arrangement of the Plant: The furnaces of the plant are always enclosed and covered by an immense steel building, and in the modern plant the furnaces are arranged end to end in a long row along the center of this building. That part of the floor of the building along the front, or charging side, of the furnace is called the charging floor. On this floor and next to the furnaces is laid a narrow, or sometimes a standard, gage track on which the solid materials are conveyed to the furnace for charging, while, back of the narrow gage track, there extends a very wide gage track, with a spread of about twenty feet, for the charging machines. The space above this floor and the furnaces is spanned by two or more electric overhead cranes. The remaining floor space of the building lying along the tapping side of the furnace is called the pouring floor, and is also spanned by electric cranes. These two floors may be on the same level, as in some of the older plants; but all the new plants are of the **two-level** type, that is, the pouring floor lies some twelve to eighteen feet below the level of the charging floor. The pouring platforms, six to eight feet wide and about eight feet high, are located along the outer edge of the pouring floor. The mixer and cupolas are often located at one end of the open hearth building, as this arrangement permits the transfer of the hot metal to be made with the cranes. However, in large plants this arrangement would be inconvenient, as it would interfere with the work of the cranes, so the hot metal is carried to the different furnaces on a track laid on the charging floor. With this arrangement the mixer may be located at any convenient point. When producer gas is used for fuel, the producer plant is built back of the open hearth plant, parallel to the charging floor. The calcining plant, stock yard, and mould yard are located at points as convenient to the open hearth house as possible. The stripper should be placed so that the steel is always advancing toward the soaking pits of the blooming mill, though this matter is but a question of convenience.

SECTION III.

CHIEF FEATURES OF OPEN HEARTH CONSTRUCTION.

Plan of Study: In order to save space and avoid useless repetition, the following description of the open hearth is made to serve for both basic and acid furnaces. Such a procedure is permissible, because both are similar with respect to form and arrangement of their parts, the chief differences being in the kind of materials used in constructing their hearths, or bottom parts. Since in this country the basic process is the more important, at least from a tonnage standpoint, this description is based on the basic furnace, and only such parts of the acid furnace that require different materials for their construction will be described.

Parts of the Open Hearth Furnace and Their Arrangement: The parts of the furnace and their arrangement are shown by the cut on the next page. From this illustration, it will be observed that an open hearth furnace consists of the furnace proper, containing the covered laboratory, hearth or bath, in which the charge is placed; ports for admitting the gas and air over the charge; regenerative chambers, containing checker brick for storing up heat from the products of combustion and imparting it to the cold gas and air; flues and uptakes, connecting the checker chambers with the furnace proper; slag pockets, which are located at the base of the uptakes; flues, leading from the air and gas supply (if producer gas is used) to the checker chambers, with connections to the stack; valves for regulating the direction of flow of gas, air and waste gases; and the stack itself. The furnace proper is located on the level of the charging floor and rests on a concrete foundation. The slag pockets, checker chambers, flues and valves are all located in a cellar, on a level about fifteen feet below the charging floor in houses of the one level type, or on the first floor level in the two level type. The checker chambers are not located under the furnace proper but under the charging floor in front of it, and the stack is placed a short distance beyond. The base of the stack flue sets on a level with the bottom of the checker chambers, but the stack proper begins at the charging floor level.

The Furnace Proper: The furnace, itself, is a rectangular brick structure, supported on the sides and ends by vertical steel buck-stays in the form of channels or slabs, four to five and one half inches thick and eleven inches wide, and bound together at their tops, both longitudinally and crosswise, by stays and tie rods. The most recently constructed furnaces have a capacity rated at 100 tons. Such a furnace is approximately eighty feet in length and twenty feet in width, outside dimensions over all. Ten sets of buck-stays on the front and rear sides, and four or six sets on the ends are required to furnish the requisite support

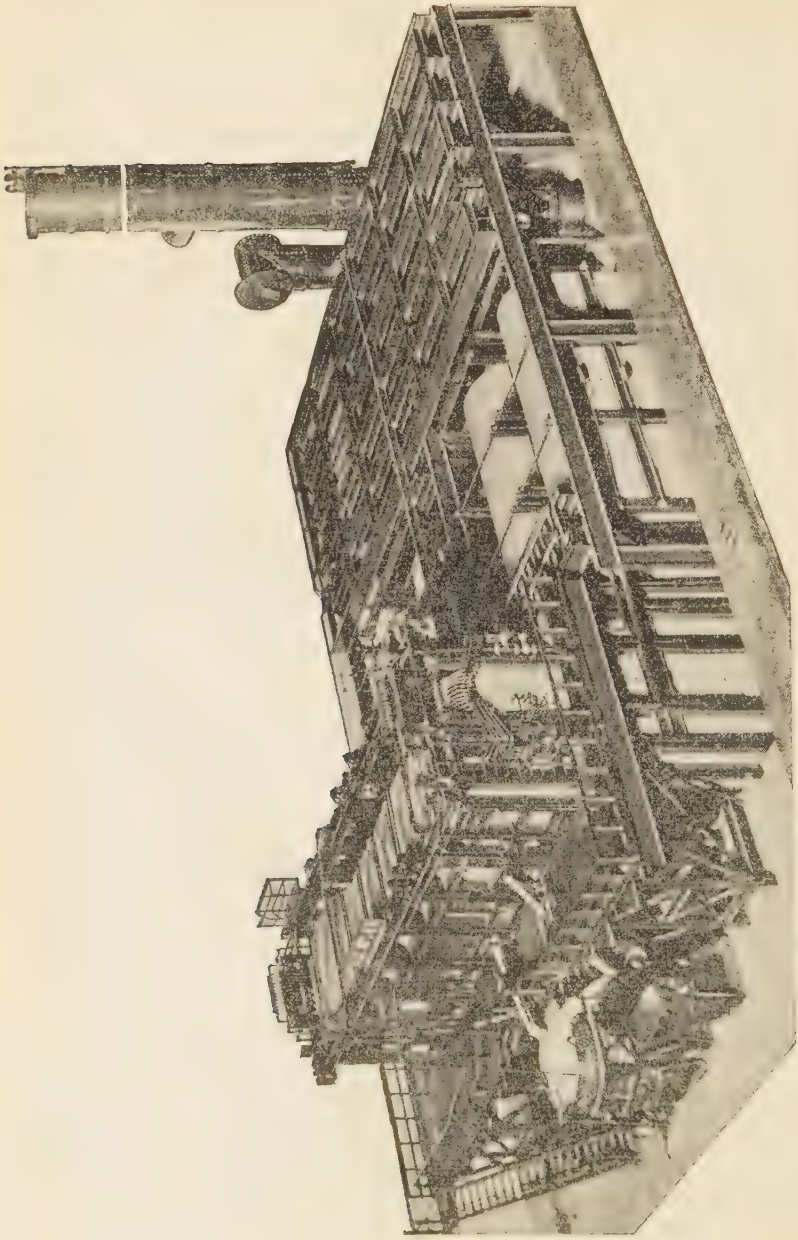


FIG. 82. Model of 100-Ton Producer Gas Fired Open Hearth Furnace. View from Tapping Side.

against expansion of the brick work. The buck-stays are held in place by 12-inch channels placed at their tops. These channels extend entirely around the furnace, those along the sides being securely tied with bolts and clamps to those crossing the ends of the furnace. The front and rear buck-stays are united by tie-rods which are two and one-half-inch steel rounds; the ends of these extend through the buck-stays and are threaded to receive nuts to hold them in place so that they can be tightened and loosened according to the expansion and contraction of the furnace. The foundation under the furnace proper is built of concrete, and is of such depth and shape as to bear the superimposed load with reasonable safety. It is usually in the form of two large piers, with an arched opening separating them. The furnace proper comprises the hearth, the side walls and the roof, the construction of which is shown in Figs. 83 and 84.

The Basic Hearth is constructed as follows: On top of the concrete foundation is placed a layer of three feet or more of second quality fire brick, and upon these is laid a two-foot layer of first quality fire brick in which a number of 15-inch I-beams are placed to act as a bottom anchorage for the vertical buck-stays which surround the furnace; a nine-inch layer of magnesite brick is then laid on top of the firebrick, and upon these bricks, a bottom is made up approximately ten and one-half inches thick with a mixture of burned magnesite, 75 per cent., and ground basic slag, 25 per cent., which is sintered into place. Dolomite may be substituted for the magnesite, but in this case the bottom must be much thicker than when magnesite is used. When complete, the hearth has the form of a shallow dish whose sides extend up to the level of the charging doors. In order to obtain this shape the succeeding courses of magnesite brick are stepped back, until the normal thickness of side wall, about thirteen and one-half inches, is reached. The exact hearth dimensions, inside, between fifteen and sixteen feet in width and about forty feet in length, are dependent upon the desired maximum capacity of the furnace and incidental features. The depth is such that the bath of molten metal will be from twenty to twenty-four inches deep. The back wall of the hearth is pierced at its exact center for the **tapping hole,** which is about eight inches in diameter and is provided on the outside with a removable cast iron lip for receiving the end of the **steel spout,** the function of which is to conduct the molten steel from the furnace to the steel ladle at the time of tapping. The **slag hole** is placed about fifteen feet from the tap hole and near the upper edge of the hearth. It is surrounded with magnesite brick and is provided with an iron casting at its base for the attachment of the cinder spout.

The Walls, in the case of basic furnaces, are begun on the top course of magnesite brick that surrounds the upper edge, or brim, of the hearth. They are built of silica brick, are about thirteen and one-half inches thick and extend to a distance of about eight feet above the charging floor level. The back wall is built up solid except for the tapping hole and slag hole,

but the front wall contains the arched doorways for charging. The doors are usually five in number, the middle one being in the middle of the furnace, and are so placed that their bases, or sills, are a few inches above the slag line. Each opening is provided usually with a water cooled cast steel frame, placed between two buck-stays to which it is fastened, and is closed by a water cooled, fire brick lined cast iron or steel door that may be lifted vertically either by hydraulic or electric power. A wicket, or peep hole, is placed on the center line near the bottom of each door.

In Acid Hearths the magnesite brick in the bottom and banks are replaced by silica brick of the best grade, and the magnesite mixture by silica sand, which is fritted upon the bottom as described in Section VIII.

The Roof over the hearth is made of silica brick, about twelve inches thick, and is arched from front to back only in the newer furnaces, but sometimes, also from end to end in older types. The roof is built independent of the walls, and rests on **skew back brick** set in water cooled skew back channels that are riveted or bolted to the buck-stays of the furnace.

The Bulk Heads which form the ends of the hearth below the ports were originally built of solid brick work and were a source of much trouble, as they burned out rapidly. These difficulties were all avoided by replacing much of this brick work with a large, hollow cast steel box with open ends to provide for air cooling. In the case of basic furnaces, the inside surfaces of these bulk heads are made of magnesite brick. The back walls of the up-and-down takes, opposite the ports, are also known as **bulk heads.** They, too, are subjected to much erosion, but no means of entirely overcoming the rapid wearing away of these bricks has been found.

The Ports: The air and gas ports at each end of the furnace are built at an angle to the bath, so that the flame is directed against the bath and away from the roof. In order to protect the roof and promote the mixing of the gas and air, the air enters above the gas. The bricks separating the two ports are protected by a water cooling system. Where natural gas is used, unless the furnace was constructed for producer gas, there is but one port at each end of the furnace, the gas entering on each side of either end of the furnace behind a bridge wall, which extends across the furnace in front of the well, or up-take, from the checkers. This wall is usually made of magnesite brick, though chrome brick is well suited for the purpose, and is about thirteen and one-half inches thick and nine inches high.

The Up-and-Down-Takes are the vertical flues which connect the air and gas ports with the **slag pockets** and the fan-like flues leading to their respective checker chambers. They are built of silica brick and are not water cooled. In producer gas fired furnaces there is a pair of up-and-down-takes for air at each end of the furnace, the two in each pair being at opposite sides of the furnace. The up-and-down-takes for the gas rise with their centers coincident with the center line of the furnace and may

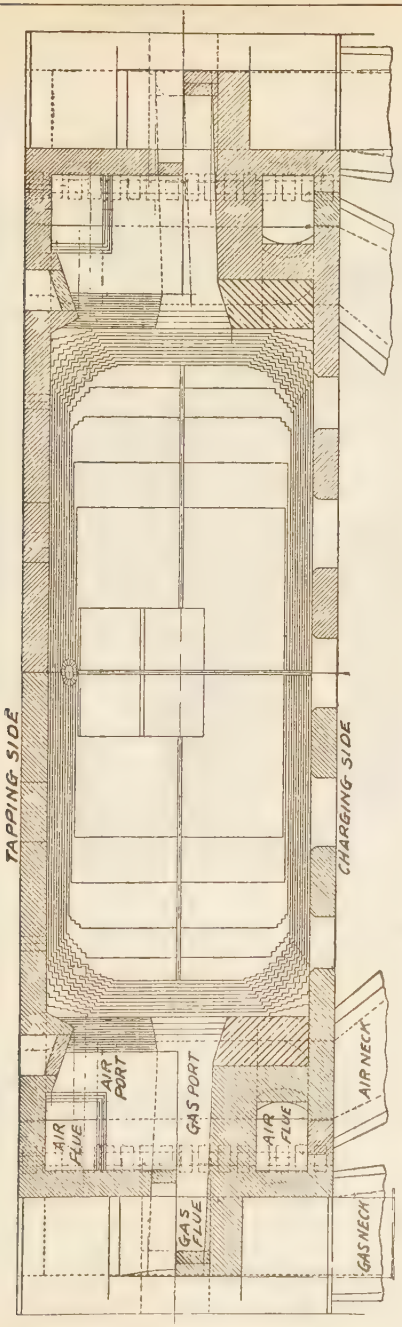


FIG. 83. Horizontal Section of 100-Ton Basic Open Hearth, Producer Gas Fired Furnace at Level of the Gas Ports.

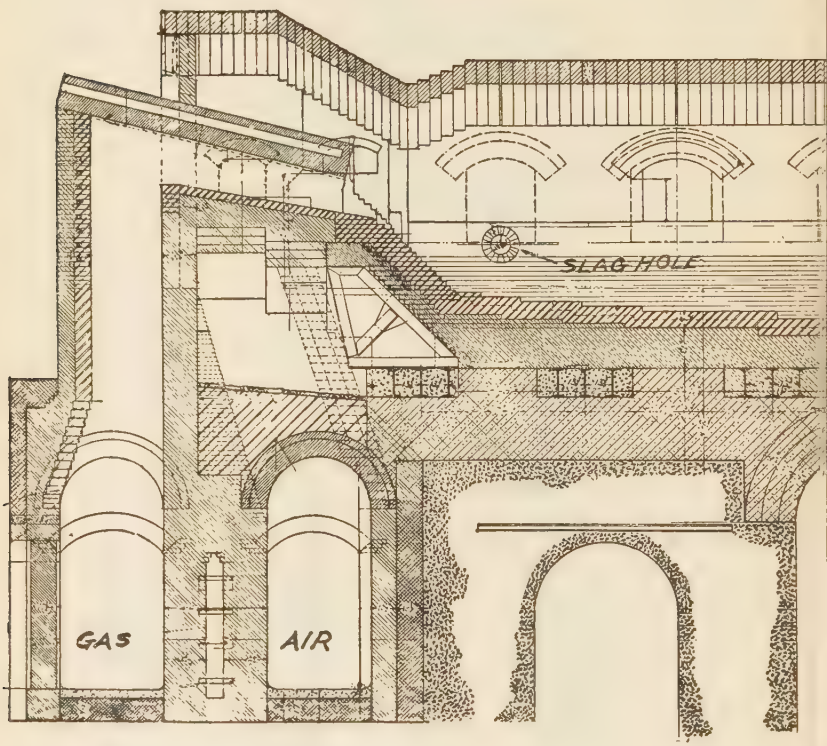
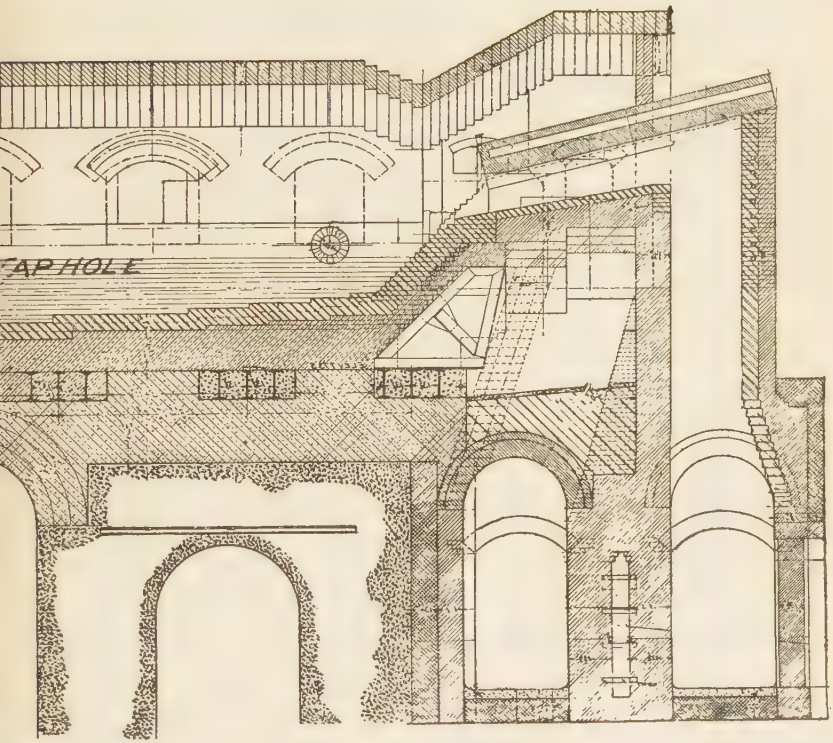


FIG. 84. Longitudinal Vertical Section of 100-Ton Basic Open Hearth, Producer Gas



Fired Furnace, Showing Slag Pockets, Flues, Ports and Hearth.

stand out with three walls exposed, designated as the **dog-box type,** or be built in between the air flues. For a 100-ton producer gas fired furnace these flues are each four feet by three feet, inside dimensions.

Arrangement of Up-and-Down-Takes for Natural Gas, Coke Oven Gas, Pulverized Coal and Tar: The construction of the up-and-down-takes in a natural gas fired furnace is much simpler, as it is only necessary to have one up-take for the air at each end of the furnace. This up-take in modern furnaces is circular, with a diameter of about six and one half feet, and is therefore called the **well.** The air, as it rises, is deflected downward toward the bath by the port, which is arched from front to back but is straight, longitudinally, with a downward slope toward the hearth. This roof is usually about nine inches thick, except near the neck where it joins the roof of the furnace. Here it increases to twelve inches on account of this point being subjected to the greatest wear. The bridge wall previously described, which crosses the port adjacent to the up-take, causes the incoming air to roll down past the opening from the gas pipes, one of which enters at each side of the port. Thus, there are in all four pipes to a furnace. These gas pipes have a diameter of four inches. The main supply pipe usually passes over an entire row of furnaces. A branch line, provided with a meter, a valve, and a three-way cock, leads to each furnace, where it again branches into the four-inch pipes which enter the ports. For tar and pulverized coal the same construction as for natural gas has been employed, because, so far, these substances have been used only as a substitute for the latter fuel when the supply became low. Both these substitutes are introduced into the furnace by inserting the nozzles of the burners through small openings in the brick work closing the ends of the furnace, one burner at each end of the furnace being required.

Slag Pockets: The slag pockets are chambers at the bottom of the up-and-down-take flues. Their functions are to serve as flues to conduct the gases to and from the checkers and to catch any solid matter carried over with the products of combustion, thereby preventing most of this slag material from reaching the checkers and clogging them up. The pockets are designed large enough so that only in extreme cases do they have to be cleaned out more than once every run. In the 100-ton producer gas fired furnace, they are about three feet six inches wide, and eight feet high. The two at each end of the furnace are separated by a three-foot silica brick wall. The outside walls are two feet seven and one half inches thick for the air, and three feet for the gas side; the former have an inside lining of silica brick, set against first quality fire brick, while the latter is made of silica brick only. The floor and roof are covered inside with silica brick, the latter being arched on a radius of half the width of the pockets. One end of each pocket merges into a short, fan-like flue, called a **neck,** which leads to the top of its regenerator chamber.

Regenerators for Producer Gas: The regenerators, of which there are two pairs to a furnace, are built out in front of the furnace and under

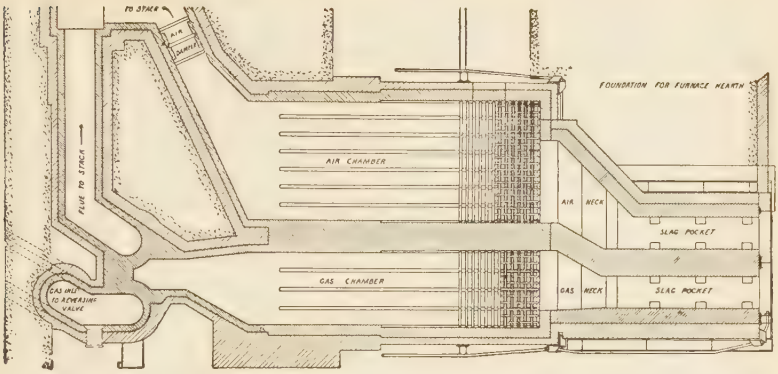


FIG. 85. Horizontal Sections through Checker Chambers and Flues to Furnace and Stack.

the charging floor, about half below and half above the casting floor level. They are separated from the furnace by a distance of about four feet. Each pair is made up of one checker chamber for gas and one for air, arranged so that the outer wall of the gas chamber is nearly in line with the end of the furnace. The gas chamber is always smaller than the air chamber, because the larger volume of air is necessary to burn the gas and assist in the oxidation of the bath. The total space actually occupied by the checkers in all four chambers is from 120 to 150 cubic feet per ton of

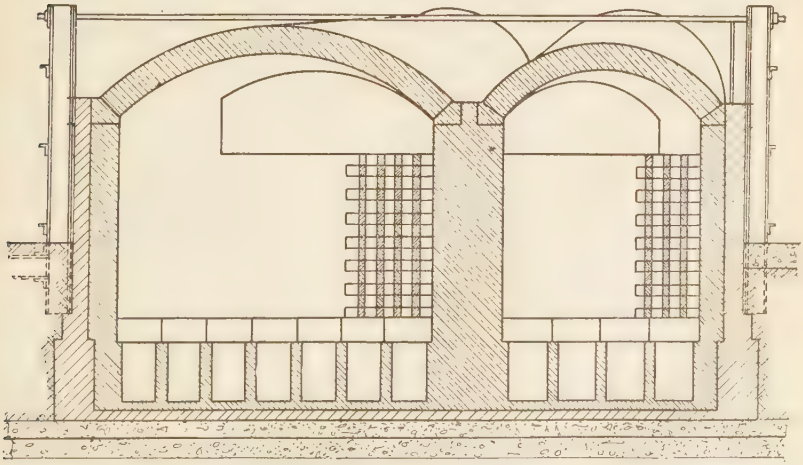


FIG. 86. Cross Section through a Pair of Checker Chambers, showing Rider Walls and Method of Laying Checker Brick.

furnace capacity. For a 100-ton furnace the volume of the checkers in the air chamber is between 3500 and 3600 cubic feet while the corresponding volume in the gas chamber is between 2500 and 2600 cubic feet.

The gas chambers on such a furnace, measured inside, are about thirty-one feet long, eight feet wide and sixteen and one half feet high from the bottom to the base of the roof, which is arched to rise twenty-three to twenty-five inches higher. The air chambers are of the same length and height, but are about eleven and one half feet wide, and the arch in the roof rises about thirty-four inches. The walls of both gas and air chambers are built usually with nine or thirteen and one half inches of common brick on the outside and thirteen and one half inches of first quality fire brick on the inside, and are reinforced on the two sides and the free ends by channel buck stays and tie rods. At some plants the two chambers in a pair are built en bloc with a single dividing wall between them. In this plan of construction the dividing wall is about three feet thick and is built entirely of first quality fire brick. The floors of the chambers are started usually with a nine-inch layer of concrete, which is followed with a heavy coat of pitch as a water proofing. On the pitch is laid another nine-inch layer of concrete, then four and one-half inches of common brick and four and one-half inches of first quality fire brick. On this floor, are laid nine-inch fire brick rider walls, which divide the gas and air chambers longitudinally into three and four flues, respectively, to a height of about four feet. These walls are spanned by fire brick tile, size, about 3″x12″x31″, which are spaced center to center a distance equal to the length of the checker brick. On these tile, the checker work, of best quality fire brick, is begun and continued to within about three and one-half feet of the top of the gas chamber, or to within about four feet of the top in the air chambers. The most common size for the checker brick is 4½″x4½″x10½″, but other sizes are frequently found in use, also. The arched roofs of the regenerators are of fire brick, and thirteen and one-half inches thick. The checker work is separated from the flues leading to the slag pockets by a solid wall which rises to their top. This wall aids much in preventing slag and dust from being carried into the checkers. But in spite of all precautions, some dirt is carried over into the chambers, which causes them to become choked eventually, when the furnace must be closed down until the checkers are cleaned or replaced.

Regenerators for Natural and Coke Oven Gases: At some plants where natural gas or coke oven gas is used, as for example at Homestead and Clairton where natural gas was originally the only fuel employed, the gas chamber, in addition to the regular air chamber, is utilized to preheat the air. The original idea was to construct the regenerative chambers so that in case gas producers were built, the change in fuels would not necessitate a rebuilding of the furnace; but, now, the chambers are all being constructed in this manner, because it was found that when two air checkers at each end of the furnace are employed, better results are obtained than

when only one large chamber is used. Where one large checker is operated, the air and stack gases, instead of flowing to all parts of the chamber, tend to take a direct course through the center, thus markedly decreasing the efficiency of the chamber.

Regenerators for Pulverized Coal: The use of pulverized coal for fuel introduces a serious difficulty in the operation of the regenerators because of the large percentage of ash that is carried over into the chambers by the draught. This fume soon clogs the ordinary checkers to such an extent that they are no longer efficient. Two different types of regenerators, namely, the arched and columnar types, designed with the idea that they would permit the ash to be cleaned out of the chamber without tearing out the brick work, have been tried; but as the ash fuses upon the bricks, these schemes are impracticable and have consequently been abandoned in favor of the old style of construction. But instead of the usual checker brick a large tile, measuring about 24″x9″x4″, has been substituted, which gives larger openings for the passage of the gases. This construction appears to be much more satisfactory than either of the others that have been mentioned.

Flues and Valves: While the openings into the slag pockets are at the top of the checker work, the openings for the ingress and egress of gases at the opposite end of the checker chamber are at the bottom. Here the small flues formed by the rider walls open into a large one which leads to the stack flue in the case of the air chambers, or, in the case of the gas chambers, to a three-way water sealed valve, one of the best types of which is represented by the Ahlen valve. Another branch of this valve leads to the stack and the third to the gas main. These valves, together with the dampers and mushroom valves in the flues from the air chambers, supply the means by which the reversals of the flame are made. In the modern furnaces, these valves and dampers are connected so that the reversal of the air and gas currents take place simultaneously. All the valves and dampers are controlled from the charging floor. Since natural gas, and also coke oven gas, cannot be preheated without decomposing them, the valve system in furnaces using these fuels, as well as those using pulverized coal, is much simpler than for those using producer gas.

The Stack: The stack for each furnace must be of such size and height as to supply sufficient draught to the furnace. It is lined with first quality fire brick, and usually has an inside diameter of 5 feet and a height of from 140 to 160 feet above the charging floor. The shell is made of 3/16-inch boiler plate. It usually rests on a concrete foundation, on the same level as the floor of the checker chambers, and at this level it has openings for flues from the gas and air chambers, as previously described. For controlling the draft a damper is placed in the main flue at its entrance to the stack. With new or clean checkers this damper partly closes the main flue, but as the checker becomes clogged, it is raised from time to time as required.

SECTION IV.

OPERATION OF A BASIC OPEN HEARTH—PURIFYING THE METAL.

Plan of Study: In the preceding section it was stated that, so far as construction goes, the only important difference between acid and basic furnaces is that, while the basic process requires the bottom and banks of the furnace to be of basic materials, the acid process requires a bottom and banks lined with silica brick and sand. There is, however, a great difference in their operation and in the raw materials used for each—so great, indeed, as to make a separate treatment of the two processes from this point very desirable. As the basic open hearth is the leading steel-making process in this country, it will be described first and somewhat more in detail than the acid.

Furnace Attendants and Their Duties: For the work on each furnace, three men, a first helper, a second helper and a cinder-pit-man, are needed, and besides these, there is a foreman, called a melter foreman, in charge of a number of furnaces. Ordinarily, the first helper has charge of the furnace except at the tapping of a heat. He informs the charging machine operator of the amount of ore the charge will require and how and where to place the various parts of the charge; he regulates the heating of the furnace; runs off the slag; directs any repairs necessary during the operation; and has charge of **working the heat,** that is, making the necessary additions of ore, pig, spar, etc. to prepare the steel for tapping. But when the heat is ready to tap, the melter foreman takes charge. The first helper, subject to the supervision of the melter, actually taps the heat, and, after doing so, he directs the repair of the bottom and helps make up the banks and clean up the steel spout. The second helper is next in charge; he keeps a supply of dolomite, feed ore, fluorspar, ferro-manganese and ferro-phosphorus on hand, and places the solid recarburizing additions on the platform convenient to the ladle. He helps to work the heat, digs the plug out of the tapping hole when the heat is ready to tap, keeps the tapping hole open and clean while the furnace is being rabbled, and assists in making up the banks of the furnace preparatory to recharging. He also attends to the plugging of the tapping hole, relines the steel spout after each heat and cleans up around the furnace. The cinder-pit-man attends to the cleaning of the pits, from which the slag and metal must be removed after each heat. In addition, he assists in making bottom at his own furnace and all the others under his melting foreman. The melter, or foreman, usually has charge of a group of six or seven furnaces. He takes charge of any furnace in his group when any serious difficulty arises, and he always has charge of the tapping of the heat. He receives an order for the kind of steel desired from the steel distributor, so when the tapping time of a heat is near, he orders the recarburizer and moulds necessary, and takes charge

of the furnace when the carbon is but a few points above the tapping point. He decides when the heat is ready, gives the order to tap, and directs the addition of the recarburizers. He gives the order for lifting the ladle when the steel is out of the furnace, superintends the teeming of the steel, and inspects the bottom of the furnace after the heat is out.

Preparation of the Furnace for Its First Charge: Starting a new furnace is an operation that requires a great deal of care in order to avoid injuring the brick work and to prevent explosions, especially when producer gas is used for fuel. The complete preparation of the furnace may be said to take place in four stages, known as **drying, heating, making bottom** and **washing.** The drying is begun very slowly with wood or gas fires, and requires about twenty-four hours, during which time all the connections to the stack on both ends of the furnace are left open. The temperature is then gradually increased for about another twenty hours. When the furnace has almost reached a red heat inside, the products of combustion are led off through only one set of checkers for three or four hours, then gas is turned on carefully and the real heating is begun, which requires about twenty-four hours more. During this time, the flame is reversed at intervals of about an hour at first, then more often, in order to heat up both sets of checkers evenly and uniformly. When a slag-melting temperature has been reached, finely ground magnesite is thrown into the furnace to cover the joints between the magnesite brick, and a little finely ground basic cinder is scattered on top of it. About twelve hours is required for these additions to fuse and make the bottom solid. The making of the bottom is then begun. For this purpose burned magnesite is much preferred, but as this substance is sometimes very expensive, calcined dolomite is then employed as a substitute. With the former, the procedure is about as follows:—A mixture of burned magnesite, 75 per cent., and basic cinder, 25 per cent., both ground to pass a ¼-inch screen, is scattered over the bottom and sides of the hearth to a depth of about ¼ inch, and allowed to sinter for at least three hours. Then the gas is turned off, and another layer of the mixture is thrown in; and this procedure is repeated, at proper intervals of time, until the bottom and banks have been built up to the desired thickness of about eleven inches, which occupies ten days or more. The tapping hole is next cut through from the outside, to terminate on the bottom, and is then filled up with burned dolomite, held in place by a cap of clay on the outside. The furnace is then ready for the wash heat. About twenty tons of basic cinder is charged and melted. This melt is rabbled up against the banks so that every part of the hearth is made solid, and is then tapped out. Burned dolomite is now piled on top of the banks as high as possible, when the furnace is ready to receive its first charge.

Charging: The first charge consists of limestone, scrap, and cold pig iron; neither ore nor hot metal are used on a new bottom until it shows it is not absorbing iron and is absolutely solid. **Trade heats,** of approxi-

mately half scrap and half hot metal are charged for the first half dozen heats, after which the percentage of hot metal is increased as rapidly as possible to the normal. The materials in the charges vary for different kinds of heats, but in general, a so-called Monell heat requires from 75 per cent. to 100 per cent. hot metal and a trade heat less than 75 per cent. hot metal. In each case, the remainder of the metallic part of the charge consists of scrap, while the ore and limestone are varied to suit the conditions. An example of each as used on a 100-ton furnace follows:

Monell.		Trade.	
Limestone	20000 pounds.	Limestone	17000 pounds.
Ore	40000 pounds.	Ore	10000 pounds.
Scrap	45000 pounds.	Scrap	95000 pounds.
Pig Iron	165000 pounds.	Pig Iron	115000 pounds.

In place of ore, briquettes, made from blast furnace flue dust, or heating furnace cinder may be substituted. The charge, with the exception of the molten iron, is brought to the furnace in the charging boxes previously mentioned, and charged by machine. Hot metal is brought, either from the mixer or from the blast furnace direct, in ladles and is then poured into the furnace through a runner that is introduced at one of the doors for the purpose. Other additions in small quantities are thrown in by hand through the doors. Most plants produce some scrap in very large pieces which will not pass through the doors. At such plants advantage is taken during repairs to old furnaces to charge such large scrap through the top before the roof is put on. As to the grade of the materials in the charge, it is preferable to have an iron low in sulphur and silicon because the former element is only partly removed in the furnace, if at all, and the latter, upon being oxidized to silica, rapidly cuts away the banks. A manganese content between 1 per cent. and 2 per cent. is also desirable, as it assists somewhat in the removal of the sulphur. As there is almost a complete elimination of phosphorus in the process, the quantity of this element in the charge is not of great importance up to one-half of one per cent. As previously indicated, the pig iron, in order to save time and conserve heat, is charged in the molten state whenever possible.

The Order of Charging the Raw Materials: As to the order of charging, the limestone is always charged first for these reasons: If it were charged on top of the scrap, for example, it would act as an insulator and thus prolong the melting period; it would all go to make up a part of the first slag, which would be too thick and viscous to work well; it would be drawn off with this slag in the run offs, thus leaving very little lime in the furnace to hold the phosphorus in the latter stages of the refinement; and, finally, the benefits to be derived from the lime boil, to be described later, would be lost. Upon the limestone, will be charged the ore, or briquettes, which, if any is needed, will vary in amount according to the nature of the rest of the charge and the heating capacity of the

furnace. In order to hasten oxidation, ore may also be added from time to time during the later stages of the process. The scrap is next charged, and if cold pig iron is used, it is charged with the scrap. The gas, which is usually but partly turned on during the charging is then turned on full, and the first or melting stage begins. If hot metal is to be charged, it is not added until the melting period is well advanced.

Melting Down the Charge: Heat is imparted to the charge partly through radiation from the incandescent particles in the flame. The fuel should, therefore, burn with a full long flame reaching almost from end to end of the furnace. But the flame should never extend through the ports and down-takes, as it would then rapidly **fuse** the brick of those flues and needlessly waste the fuel. For the same reason, the flame should be directed downward from the port and not be allowed to impinge on the roof. The light scrap and pig iron, if any is added to the solid charge, begin to melt first. During the melting much of these materials is oxidized, so that there is formed both molten metal and oxides, which trickle down over the scrap to the bottom. A slight amount of molten slag and metal is thus present, on the bottom of the furnace, before the hot metal, i. e., molten pig iron, is charged. Reversals of the flame should occur every fifteen to twenty minutes during this period, and care must be taken not to overheat the roof, for too high a temperature will cause the bricks in a new roof to spall, and those in an old one to fuse. Silica brick frequently **sweat,** that is, fuse slightly, but this condition does no harm and indicates a favorable temperature in the furnace. Care must be taken with the roof and checkers in a new furnace, especially, and the temperature must be kept relatively low for the first ten heats or more, after which time the gas may be gradually increased until the full working temperature is attained.

The Addition of the Hot Metal: The molten metal can usually be added in about two hours after the charging of the solid materials is begun. The exact time for adding this metal is governed by the temperature of the solid charge. Evidently this temperature should be above, or at least as high as, that of the melting point for pig iron. This statement does not imply that the scrap, which has a much higher melting point than pig iron, should be completely melted. Indeed, a delay in the addition of the molten metal until the scrap is all melted may be very undesirable, for not only would the scrap be excessively oxidized, but the high temperature combined with the excess oxides present would result in a too violent reaction, and much foaming of the bath and loss of metal due to the rapid generation and evolution of carbon monoxide would result.

The Purification Periods: The purification of the hot metal, after it is introduced into the furnace, is brought about through the oxidizing influence of the iron oxides and the fluxing properties of the limestone. While both oxidizing and fluxing reactions are actually taking place in the furnace at the same time, the action of the iron oxides must be considered

as preceding that of the limestone, for the acid impurities must first be oxidized before they can be neutralized, or fluxed, by the bases. It is evident that the fluxing action may immediately succeed the oxidation, but the conditions set up by the manner of charging the limestone tends to retard its calcination and thus to separate the two actions. Now, the carbon monoxide generated by the action of the iron oxides upon the carbon of the pig iron is at first evolved in a manner quite different from that of the same gas formed later on in the process or of the carbon dioxide from the calcination of the limestone, and this difference is indicated by the way in which the bath is agitated. Hence, the furnacemen have fallen into the habit of speaking of the purification as taking place in stages, known as the **ore boil, the lime boil,** and the **working period.** The third is the stage that follows the complete calcination of the limestone. In order that the reader may understand what is implied by these terms, the changes that occur during the purification of the metal are discussed under these three headings.

The Ore Boil: Proper chemical testing will show that the purification of the molten iron begins immediately after it is charged into the furnace, and, with the exception of carbon, the oxidation of which is not completed till the heat is ready to tap, progresses very rapidly. So, in about two hours practically all of the silicon and the greater part of the manganese will have been oxidized, and the former, then in the form of silica, will have been neutralized, some with lime, but the greater portion with the oxides of iron and manganese, and will have become slag. Some of the sulphur, also, will have been oxidized, particularly if the sulphur content of the hot metal was high, but as the oxides of this element are volatile and the high temperature tends to decompose the sulphites and sulphates, only a part of the oxidized sulphur is retained by the slag, and the remainder is carried off with the products of combustion. A very small portion of this element finds its way into the slag as sulphides, probably as manganese sulphide. With the silicon and manganese, the phosphorus is also rapidly attacked by the iron oxide, which not only oxidizes it, but neutralizes the resulting oxides of this element. These iron phosphates, which are easily reduced, likewise pass into the slag, where the iron oxide is replaced with lime, thus forming the calcium phosphates, which are very stable compounds. During all this time the carbon is also being slowly oxidized. This action, which at first takes place near the surface of the metal, results in the evolution of carbon monoxide in the form of tiny bubbles, which become entangled in the viscous slag and cause it to foam. Consequently, the slag, thus permeated with little gas cells, occupies much more than its natural space in the furnace. Carbon dioxide is also evolved by the limestone, which begins to be calcined more and more rapidly as the temperature at the bottom rises; but as the gas resulting from the decomposition of the limestone escapes in relatively large bubbles, it causes very little of the foaming.

The Run-off: When the slag level has been raised to a height a little above that of the bottom of the openings for the doors and is threatening to break through the dolomite dykes built up just inside these openings, the dolomite with which the slag hole is dammed is cleaned out of this opening, and the excess slag is allowed to flow through the cinder spout into the cinder pit or into a slag pot placed below to receive it. This tapping of slag is known as the **run-off.** The bases in this first slag are composed chiefly of iron and manganese oxides, the lime and magnesia being relatively low. It is not unusual for these slags to contain iron as oxide equivalent to 30 per cent. metallic iron, and as they constitute about 40 per cent. of the total slag formed in the process, they represent the source of greatest loss of metal for the entire process. Practically all of the iron contained in the run-off is in the ferrous condition.

The Lime Boil: The action of the ore and other iron oxides, formed by the oxidizing flame, upon the carbon will be somewhat violent for two hours or more, during which time the scrap will have been almost completely melted down. Gradually, however, as the carbon content decreases and the temperature of the bath rises, the ore boil subsides, or changes its character, and, the calcination of the limestone becoming more rapid, the lime boil is in the ascendency. The lime boil is characterized by a rising of the lime to the top of the bath and by a violent bubbling of the bath, caused by the rapid evolution of carbon dioxide gas from undecomposed limestone which still remains on the bottom, and also in part by the continued oxidation of carbon in the molten metal. These activities play important parts in the process. Thus, not only does the violent bubbling caused by the evolution of the carbon dioxide gas agitate the metal and slag, thus mixing them and exposing the metal to the oxidizing influence of the flame, but a part of the gas, at least, unites, directly or indirectly, with the carbon remaining in the iron to form carbon monoxide. Furthermore, by rising to the surface, the lime may replace iron and manganese oxides in the phosphates, sulphates and silicates present and thus become a part of the slag, while any excess lime is also taken up and goes to increase the basicity of the slag. This property of the slag makes it more capable of retaining both the phosphoric and silicic acids together and renders the former less liable to be reduced. During this period the flame in the furnace should be reversed more frequently (about every 15 minutes) in order that the temperature of the bath eventually will be well above the melting point of the decarbonized metal.

The Working Period: Since all the impurities except carbon have now been eliminated, the operations during this period aim at regulating the properties of slag, adjusting the carbon content of the steel, and raising the temperature of the bath to the point where the steel may be tapped from the furnace and cast into ingots before it begins to solidify. In order for the steel to be teemed without difficulty, this temperature should be

at least 150° C. (300° F.) above its fusion point. Both the chemical and the physical properties of the slag play most important parts in the basic process. In order that it may protect the metal against contamination by sulphur from the flame, retain the impurities, especially phosphorus, and promote the elimination of the carbon, the slag must contain a large quantity of active oxidizing agents, except at the end of the period, and must be strongly basic at all times. But even with the chemical composition of the slag properly adjusted, its activity will depend upon the fluidity to a great extent. The reagents at the disposal of the operator for regulating these properties are iron oxide, limestone, dolomite and fluorspar. The iron oxide is usually in the form of lump ore, though heating furnace cinder formed on a magnesite bottom to insure a low silica content may be used as well.

Methods of Working the Heat: There are two general methods of working heats, and briefly described, they are as follows: The first method is somewhat like the Bessemer, that is, the carbon content of all heats is reduced to a common point, about .10 per cent., when the steel will be tapped and the per cent. of carbon will be raised to that desired by the addition of recarburizers. In the second method the carbon is caught on the way down, that is, the carbon content is reduced to a point slightly under that required, to allow for the carbon contained in various additions, and the bath of steel is then tapped. Medium and low carbon steels are usually worked by the first method, while high carbon steels may be worked by either.

Testing for Carbon: So toward the end of the lime boil, or earlier if it appears that the carbon content of the bath is dropping rapidly, the first helper will begin taking tests in order to follow the progress of the heat. These tests he takes by securing a small test-spoonfull of the metal, which he pours into a small rectangular mould. As soon as the metal has solidified in the mould, it is removed by jarring the mould while in an inverted position; the test piece is nicked in the center, rapidly cooled with water, and then, while still warm enough to dry itself, it is broken with a heavy sledge hammer. From the fracture thus exposed, the carbon content, which determines how the heat is to be treated, can be very accurately estimated. In order that the temperature of the bath may be raised to a point sufficiently high for tapping by the time the carbon is reduced to the point aimed at, it is desirable that the carbon content of the bath at the end of the lime boil should be forty to fifty hundredths of a per cent. (40 to 50 points) higher than that desired at tapping.

Control of Carbon and Temperature: If, as occasionally happens the carbon is nearly all removed while the bath is yet too cold to tap and pour successfully, it is difficult, on account of its inactivity, to bring the heat up to the proper tapping temperature without danger of burning, or over-oxidizing, the steel, and unduly increasing the wear on the roof of the furnace.

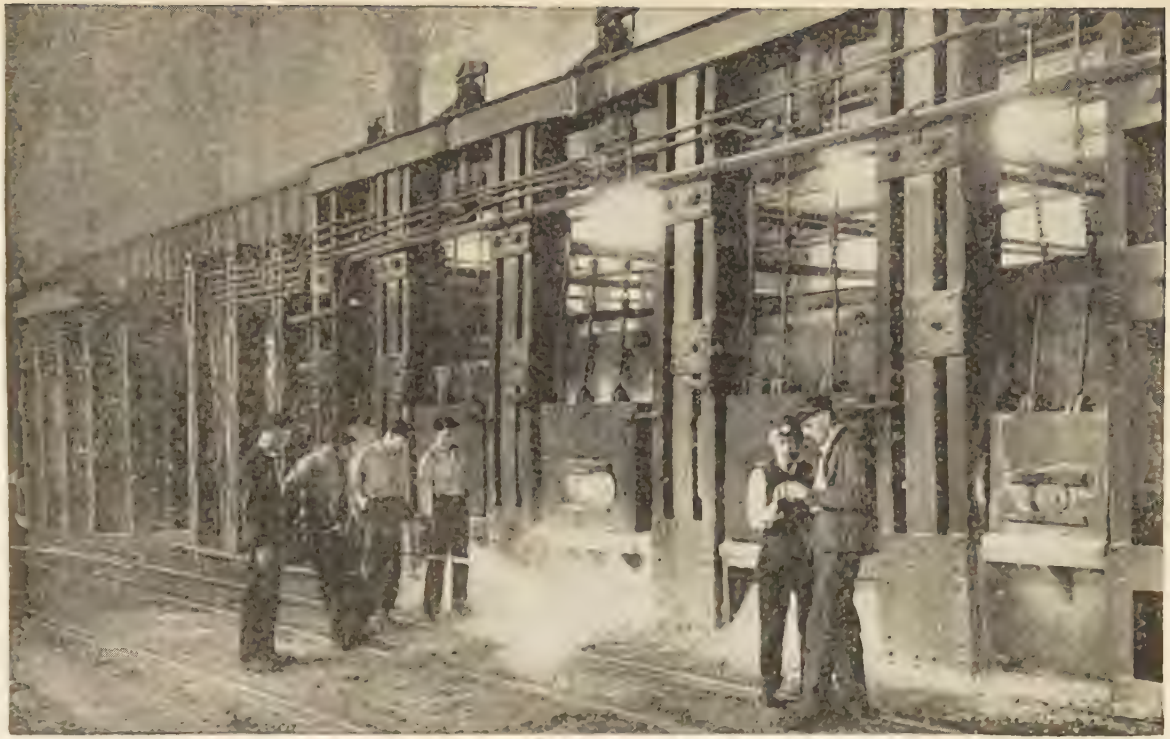


FIG 87. View of Basic Open Hearth Furnace just Prior to Tapping, showing Attendants Reading a Fracture Test (right) and Testing for Temperature (left)

A heat working under such conditions is known as a **sticker**. To prevent this over-oxidizing, **pigging up** is resorted to, that is, the carbon content is **held,** or kept constant, by adding pig iron, which also aids in raising the temperature by producing a little boil in the bath. Usually, however, there will be fifty to eighty points of carbon to be removed from the bath after the lime boil. Therefore, as soon as the first helper sees that the lime is about all up, he will first take a test, then see that all lumps of unfused matter, or **nigger heads**, are melted and that the slag is sufficiently fluid. To bring about the rapid melting of the unfused bodies and increase the fluidity of the slag, fluorspar sufficient for the purpose will be added. Then to hasten the elimination of the carbon, it may be necessary to **ore down,** that is, additions of ore or heating furnace cinder will be made from time to time as required to reduce the carbon content. After each addition of oxide has had time to act, a test is taken. During the last half hour, in some cases the last hour, the heat is in the furnace, no ore will be added. Some foremen erroneously believe that the elimination of carbon at this point may be hastened by stirring the bath with a long steel bar, a process known as **shaking down,** while others will merely allow the metal to lie in the hearth undisturbed. In the case of low carbon heats the flame will now be reversed in the furnace about every ten minutes in order to raise the temperature, and as soon as the tests show that the carbon is within three or four points of the desired content, the melter, or foreman, is notified. He takes additional tests for the carbon content and also for temperature, orders the recarburizers, inspects the furnace, ladle, etc., and completes the arrangements for tapping the heat.

Judging the Temperature of the Bath: For judging the temperature of the bath, two very simple tests are employed by the furnacemen. One of these tests consists of quickly inserting the end of a long steel bar or rod into the bath of metal and slowly moving it from side to side until the part immersed in the metal melts off. Then the bar is withdrawn, and from the appearance of the hot end the condition of the bath with respect to temperature may be judged. Thus, if the bath is too cold, this end of the rod will be pointed; if too hot, it will show nicks on the sides near the end; but if the temperature is right, the end of the rod will have melted off so as to leave a clean, square end. The second method depends upon the quite evident fact that the higher the temperature of a fluid the longer it will remain fluid in contact with cold surroundings. It is carried out simply by quickly withdrawing a test-spoonful of the molten steel from the bath and at once pouring it, rather slowly, but at a fixed rate of flow, out of the spoon. The operator judges the temperature of the steel by the way it flows and by the extent and thickness of the skull it leaves in the spoon. By long practice with these methods the workmen become very expert in making these relative determinations of temperature.

Fig. 88. View of Charging Side of Furnace at Tapping.

Tapping: The furnace should be manipulated so that a tapping temperature is reached before the carbon content has been reduced to the tapping point, as otherwise some difficulty will be experienced with high carbon steels in holding the carbon in the bath, if the carbon is to be caught on the way down, while with low carbon steels, it will be difficult to reach a tapping temperature or the metal will be over-oxidized, with the result that it will tend to be both hot short and cold short unless deoxidizers, such as spiegel, ferro-manganese, or pig iron, are added. Prolonging the life of the heat at this point in order to reduce the sulphur content is very bad practice for the double reason that the removal of the sulphur is uncertain and the cure is worse than the disease. The proper temperature for tapping low carbon heats is 1600° C., or a little higher, while for heats in which the carbon is caught on the way down, the tapping temperature may be about 100° C. lower. To accomplish the tapping, the second helper digs out from the rear the mud plug and most of the dolomite with which the tapping hole is closed, after which the hole is opened by driving outward the dolomite remaining in it by inserting a tapping rod through the wicket of the center door in the front of the furnace. Sometimes molten metal seeps into the tap hole and solidifies

there, and in that case the hole is burned out with oxygen, which is applied to the hot metal through a small pipe, about ¼ in. in diameter. The steel then flows through the hole out of the furnace and down the spout into the ladle. Since the tapping hole is on a level with the bottom of the hearth, the greater part of the steel is out of the furnace before any slag appears, and this fact permits of recarburization in the ladle. It is not advisable for the recarburizing materials to be allowed to come into contact with the slag, since some of the phosphoric acid in the slag may be reduced and the phosphorus re-enter the steel. The tapping spout and ladle are so placed as to direct the stream of molten metal a little to one side of the center of the ladle, as the swirling motion tends to mix and make more homogeneous the contents of the ladle.

SECTION V.

FINISHING THE HEAT—MAKING STEEL FROM THE PURIFIED METAL.

Methods of Finishing the Steel: The process of finishing the steel consists in making such additions as are required to produce the kind and grade of steel desired, and with few exceptions these additions are made immediately before and after tapping the heat. The methods of making the necessary additions to produce the various kinds and grades of steel differ somewhat, not only for the different grades but in different works making the same grades. For example, the ferro manganese and spiegel are preferably added to the steel in the ladle and in the molten state, but not all plants are at present equipped to melt these materials, and ferro-manganese is still generally added in the solid form. For the plain steels the methods of making additions for carbon and manganese may be briefly stated in the following tabulated form.

High Carbon Steels. (C.60% to 1.30%)

Method I. Carbon is caught on the way down; ferro-manganese is added, and coal, if needed, in the steel ladle.

Method II. The steel is tapped with the carbon at .10%; molten spiegel mixture is added in the steel ladle.

Method III. The carbon in the bath is eliminated to .10%; sufficient molten pig iron is added in the furnace at the time of tapping to raise the carbon content almost to the point desired. Then ferro-manganese may be added to the ladle to make up the deficit in the carbon, and supply the manganese deficit left by the pig iron.

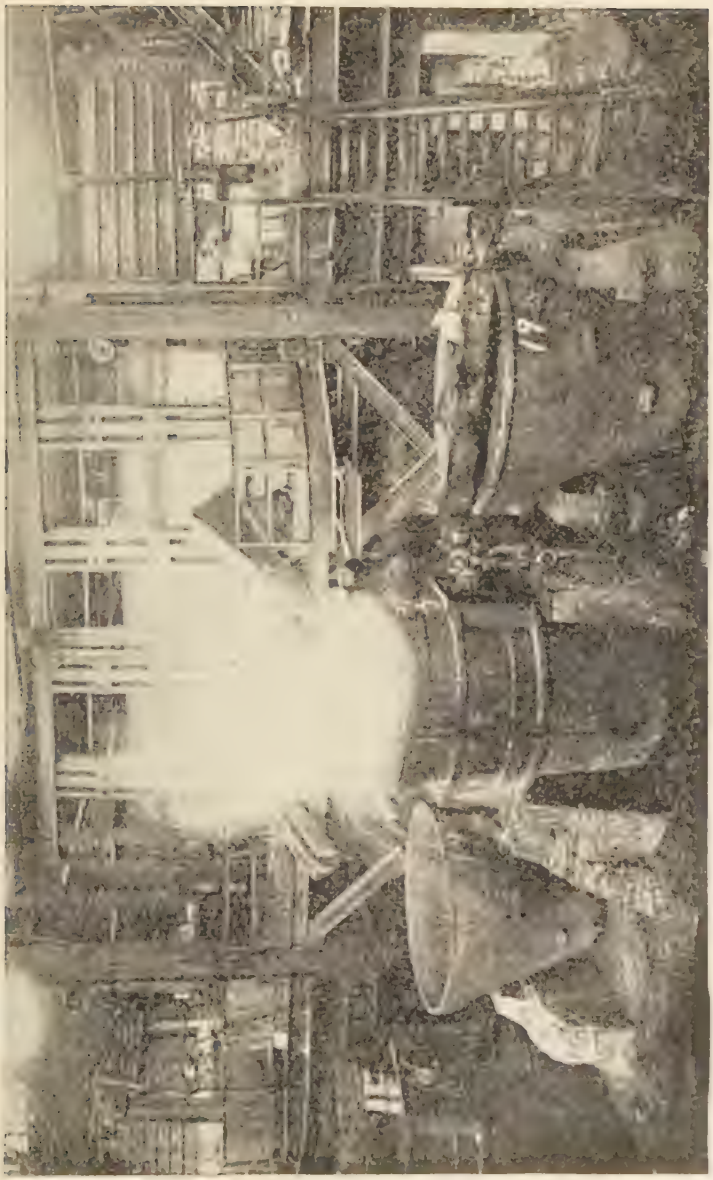


FIG. 89. View of Tapping Side of Open Hearth Furnace while Tapping Steel into Ladle.

Medium Carbon Steels. (C. .30% to .70%)

Method I. The steel is tapped with a carbon content of .10%; molten spiegel mixture is added in the steel ladle.

Method II. The carbon in the bath is eliminated to .10%; molten pig iron is added in the furnace and ferro-manganese in the ladle as in III for high carbon steels.

Low Carbon Steels. (C. less than .40%)

Method I. For dead soft steels the carbon content is reduced as low as possible without danger of over-oxidizing the steel, and ferro-manganese is added in the steel ladle.

Method II. The carbon content is reduced to .10% and ferro-manganese is added alone, or ferro-manganese and coal are added in the steel ladle. In case a large quantity of ferro is required, some furnacemen prefer to add a part of it in the furnace just before the tapping hole is opened.

Method III. For finishing very low carbon steels neither molten spiegel nor molten pig iron are used on account of the difficulty of weighing and keeping molten small quantities of these materials. But in large furnaces, pig iron may be used, if the carbon content is more than .20%, as in Method II for medium carbon steels.

Other Elements: The additions for other elements will be made about as follows:—Copper is added in the solid form to the steel fifteen to twenty minutes before the heat is tapped. Sulphur is always added before the ferro additions. Ferro-silicon is necessarily added in the steel ladle; while it is the common practice to add ferro-vanadium by dropping it into the stream of molten metal in the runner, or spout, as it is flowing into the ladle. As nickel is chemically negative to iron, none is lost in the furnace, so nickel steels are made by charging nickel steel scrap, then adding pig nickel in sufficient amount to make up the deficiency, as shown by chemical analysis, about thirty or forty minutes before tapping. The same practice may be employed in the case of steel requiring molybdenum and chromium, but a comparatively large part of the latter element is lost through oxidation in the furnace. Chromium is added in the form of ferro-chromium.

Some Features that Make the Finishing of the Steel Difficult: It requires considerable experience to finish steel properly, for there are a number of circumstances that tend to complicate the operations. For example, the addition of ferro, on account of its carbon content, will always slightly raise the carbon content of the steel, though it is primarily added to increase the manganese. Similar conditions also prevail in the use of other ferro alloys and pig iron. Again, there is always a loss of the elements added, except in the case of copper and nickel, and this loss, different for each element, will vary with any one under different conditions. Hence, the efficiency of these substances is never 100 per cent.

Furthermore, it is seldom any of the elements can be obtained in pure form for this purpose, and the substance containing the element sought may vary in its content of that element. The various substances used, their efficiencies, and the amount of each element present in the bath at the tapping of a normal heat are indicated in the following table.

Table 38. Data Relating to Materials Used in Finishing Steel.

Material Added	Element Sought	Percentage of Element in Bath	Efficiency When Added in	
			Furnace	Ladle
Pig Nickel	Ni	.00 unless Ni. scrap used	98%	Never
Ferro Chromium	Cr	.00 " Cr. " "	80%	"
Pig Copper	Cu	.00 " Cu. " "	99%	"
Stick Sulphur	S	.040	Never	66%—70%
Anthracite Slack	C	Any desired	"	44%—50%
Pig Iron	C	"	95%	Never
"	Mn	.10 to .20	50%	"
Ferro Manganese	Mn	.10 to .20	50%	85%—90%
Spiegel	Mn	.10 to .20	Never	80%—90%
"	C	.10 to Any desired	"	100%
Ferro Phosphorus	P	.010	"	75%
Ferro Silicon	Si	.00	"	65—70%
Ferro Vanadium	V	.00 unless V. scrap used	"	90%

In the following table will be found an analysis typical of each of these substances.

Table 39. Representative Analyses of Materials Used in Finishing Steel.

	Fe %	C %	Mn %	P %	S %	Si %	V %	Cr %	Ni %	Cu %
Ferro Manganese	13.03	6.80	79.35	.16	.....	.66	.....	.....	.....	.....
" Phosphorus	79.97	1.10	.18	18.00	.65	.10	.....	.....	.....	.....
" Silicon, Electric	49.44	.55	.016	.075	.018	49.90	.....	.....	.....	.....
" " Blast Fce	87.465	1.52	.42	.080	.015	10.50	.....	.....	.....	.....
" Chrome	22.05	6.36	.35	.003	.079	.48	.....	69.96	.....	.....
" Vanadium	42.65	1.58	6.25	.100	.106	10.49	37.96	.....	.....	.....
Spiegel	75.68	4.39	19.13	.053	.028	.72	.....	.....	.....	.....
Pig Nickel	.....	.....	.....	.....	.....	.....	.....	.....	97.00	.....
Pig Copper	.....	.....	.....	.....	.....	.....	.....	.....	.....	99.00
Stick Sulphur	.....	.....	.....	.....	100.00	.....	.....	.....	.....	.....
Pig Iron	94.00	3.80	1.00	.17	.030	1.00	.....	.....	.....	.....

Given the weight and composition of the metal in the bath, the desired composition of the finished steel, and the composition and efficiencies of the substances to be added, the calculation of the amounts of the various additions is a simple problem in arithmetic.

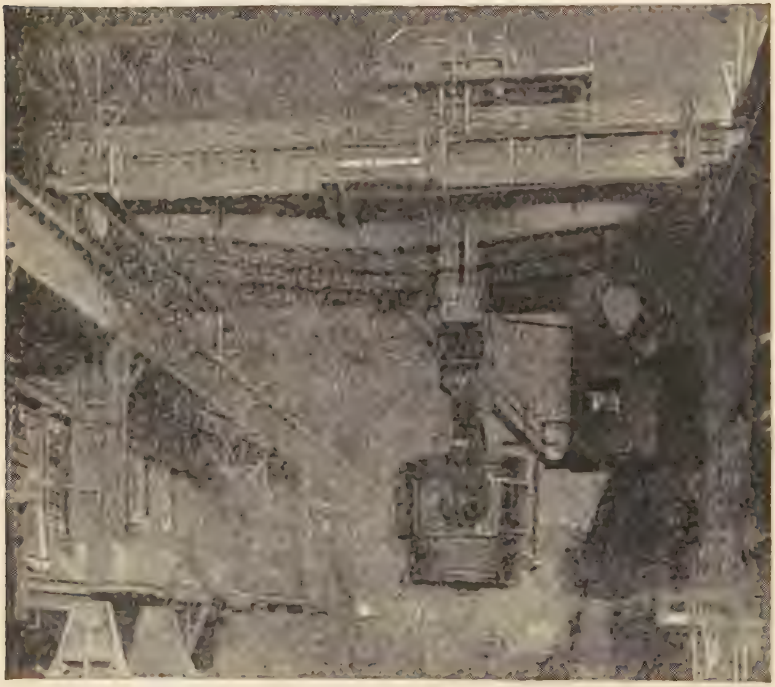


FIG. 90. View of 125-ton Crane Carrying Ladle of Molten Steel to Teeming Platform.

Teeming: As soon as the stream from the furnace no longer contains any steel, the spout, or runner, is removed, and the steel ladle is lifted by the crane and carried to the pouring platform, where the steel is teemed into the ingot moulds ready to receive it. Teeming is not to be confused with pouring. While the latter logically refers to the way the metal is let out of the ladle, usage has made pouring synonymous with casting, which refers to the manner of introducing the metal into the ingot mould. Thus, if the metal is introduced into the mould through its top, the resulting ingot is said to have been top poured or top cast; but if through its bottom by means of runners, the ingot is said to have been bottom poured or bottom cast. Teeming and top pouring are accomplished in the following manner: The ladle is placed with

its nozzle over the center and about a foot from the top of the first mould in the mould train, when the stopper is raised and the steel flows through the nozzle into the mould below. In teeming the heats, care must be taken that neither the stream of metal nor any part thereof be allowed to strike the sides of the moulds, for these splashes of metal will adhere to the mould, which quickly chills them, and, being coated on their surfaces with a film of oxide, they may cause ingot defects which later appear as slivers in the rolled steel. As the first mould is filled, the stream is stopped, and by means of a hydraulic pusher the train is moved forward so as to bring the next mould under the nozzle of the ladle. At some plants the teeming is done from an overhead crane, which moves the ladle from mould to mould. After the ladle has been emptied of steel, the slag remaining in it is dumped into cinder cars and ultimately conveyed to the cinder yard. In the meantime, the mould train is hauled to the stripper. On soft steel and special heats, unless there is a high percentage of manganese or silicon present, aluminum is thrown into the moulds, about two ounces to each ton, in order to further deoxidize and quiet the steel. Aluminum is especially effective in overcoming wildness because of its strong tendency to combine with oxygen. Of this small amount added practically none remains in the metal, so that this aluminum exerts no influence as an alloy in the steel.

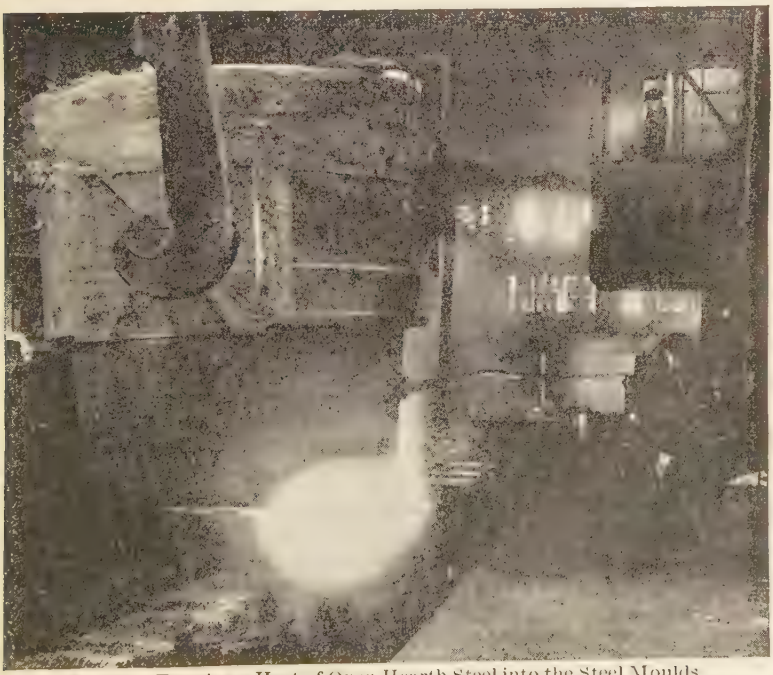


FIG. 91. Teeming a Heat of Open Hearth Steel into the Steel Moulds.

Sampling: The sampling of the heat for chemical analysis is accomplished when the heat is half teemed by slackening the stream from the ladle, whilst a spoon of suitable size is held under the nozzle and filled with the molten metal, which is immediately poured into a test mould specially designed for the purpose. The test mould may be of either one of two types, which careful and extensive experiments have shown to give test pieces most uniform in composition and most free from blow holes. One of these types is a split mould that gives a test piece having a section 1½ inches square and a length of nearly 5 inches, with a flared opening about 2 inches deep to facilitate pouring. The other type is a small cup shaped mould that gives a test piece 3¾ inches in diameter at the top and 2½ inches at the bottom with a depth of 2¾ inches. Upon being taken from the mould, the test piece is immediately stamped with its heat number, and is then delivered to the chemical laboratory for analysis. Experiments have shown that a sample taken in this way most nearly represents the average composition of the heat.

SECTION VI.

KEEPING THE FURNACE IN REPAIR.

Preparation of the Furnace for the Next Charge: After the runner is lifted and thus detached from the furnace, the cinder and any steel that remains in the furnace flow out of the tapping hole into the cinder pit. The second helper must keep the tapping-hole open until everything that can be removed from the furnace has flowed out. Fluorspar is usually thrown in on the slag left to be sure that it flows out and does not build up on the bottom of the furnace. Often, holes will be found in the bottom, due to the intrusion of steel below the surface, which, boiling there, brings up part of the basic material forming the bottom. Slag and steel are found in these holes after tapping and must be rabbled out, so that the bottom can be properly repaired. After all the steel and slag are removed from these holes, they are filled up with dolomite. The gas is left on to keep the slag and steel fluid during this process; but is shut off as soon as the repairs to the bottom have been completed. Proceeding to the next step, the second helper and cinder-pit man remove the steel that has chilled in the tapping hole, rake out and free the hole of iron and close it up with dolomite. A plug of clay is used to seal up the outside of the hole and hold the dolomite in place. The banks, which have been cut by the slag from the heat just out, are repaired by throwing burned dolomite on them (3000 to 4000 lbs. is used after each heat in a 100-ton furnace); and the furnace is then ready for charging again.

Furnace Troubles: In the operation of a furnace, troubles of a very serious nature may occur at any time, unless the furnace is watched closely, and carefully handled. These troubles present so many possibilities and are so varied that space will permit of little more than an enumeration of some of the more serious ones here. Thus, the tap-hole may break out prematurely if it is not properly tamped and capped, or it may become hopelessly clogged if it is not properly cleaned after each heat. Sometimes, sections of the bottom become detached and rise, due to the buoyant force of the metal, and when this occurs the heat must be tapped at once, and no more heats may be charged until the damaged bottom is repaired. The ports require constant attention to prevent them from building up or melting down, and thus changing the angle of the flame, which would then tend to over-heat some part of the furnace and would be rendered less effective in heating the bath. Leaks may occur in the walls of the up-and-down-takes, which result in the gas being burnt in part before it reaches the hearth. The walls and roof often wear out long before the rest of the furnace needs repairing. Roofs usually last for about 300 heats. The roof can be repaired in a few hours, and a cave-in of the roof is of a serious nature only when it falls in near the end of a heat. The most disastrous mishap that can occur to a furnace is a break-out. Breakouts may be caused by several things. A hole near a bank may not have been noticed or may have been insufficiently repaired, in which case the steel works down into it and gradually makes it deeper, until, finally, the metal finds its way through the wall and out of the furnace. Sometimes, owing to a thin spot on the banks or to slag having reached above them and worked down into them, the slag gradually cuts its way out through the walls, in which case it is usually followed by steel, as the hole soon becomes low enough to reach the bath. Such mishaps are also known as break-outs and are always of a serious nature. Once a break-out occurs, the tapping hole should be opened immediately, and as much as possible of the steel gotten into the ladle or cinder pit. The spread of cinder and metal upon the floor where the break-out has occurred can be limited usually by throwing dolomite around it. Finally, after about 600 or 700 heats, the checker work has become so badly clogged and the brick work is so eaten away, that it becomes necessary to close down the furnace for general repairs, during which the greater part of the brick work may be torn out and rebuilt.

Repair Materials: It is evident that, for making up the bottom and for doing the repair work about a furnace, much depends upon the materials employed. Great care must always be exercised to see that they are of the right chemical composition, and best suited for the work in hand, as, otherwise, the best of workmanship in making the repairs will go for naught. Therefore, a few remarks in this connection should be of interest.

Dolomite is found in local deposits similar to those of limestone. Like the latter it varies in composition through quite wide ranges, but that

suitable for open hearth work will have, after being calcined, approximately the composition shown by the following chemical analysis: Silica, SiO_2, 1.66%; Iron Oxide, Fe_2O_3, .94%; Alumina, Al_2O_3, 1.24%; Lime, CaO, 50.01%; Magnesia, MgO, 35.26%.

Magnesite: The magnesite used before the European war was imported from Madelein and Budapest, Austria, and was brought to the mill already burned and ground. It was used on the furnace bottom, banks and ports, and in repair work. An average analysis of thirty-eight cars of the imported material is as follows:—

SiO_2	Fe	Mn	Al_2O_3	CaO	MgO	Ig.Loss
2.07%	6.00%	.37%	1.63%	3.81%	84.11%	.52%

With the outbreak of the war the foreign supply was cut off, but the demand was soon met by opening deposits found in the State of Washington, and the eastern part of Canada. This domestic magnesite is purer than the imported, and for that reason it does not sinter, or bond, so rapidly, but by mixing a little of the proper fluxing material with it, this drawback was readily overcome. However, mainly for commercial reasons, the use of the imported material has been resumed, and practically the entire supply is being imported again.

Chrome Ore: Chrome ore has always been imported, as the limited deposits so far discovered in the United States and Canada are of an inferior grade. It is received in the form of small lumps. It is ground and mixed, in a wet pan, with one-half magnesite, and is used in repair work where a neutral substance is required, such as in patching flues, tapping holes, ports, etc. An analysis of an average sample of a satisfactory grade of this ore gave these results:

SiO_2	FeO	MnO	Al_2O_3	MgO	Cr_2O_3	Ig. Loss
9.02%	13.50%	.80%	10.32%	19.89%	42.66%	2.92%

Besides these materials, some ganister may be employed at some of the works, while all plants will use large quantities of loam and of fire clay for lining furnace spouts and ladles, for making up stoppers, and for other repair work of minor importance.

SECTION VII.

CHEMISTRY OF THE BASIC PROCESS.

Some of the Principles and Conditions Involved: Having followed the procedure of making steel by this process, the reader should be interested in a discussion of a subject, which to the metallurgist, at least, represents the most interesting and profitable part of the study, namely, the chemistry of the process. In beginning this study it should be recalled that the purification of pig iron, which is the first of the two main steps in making steel, includes the elimination from the metal of the four elements, silicon, manganese, phosphorus and carbon, and that the principle underlying the means by which this elimination is effected is that of oxidation. In basic open hearth processes, the elimination of sulphur may also take place

to a greater or less extent, depending upon the amount present, but is never to be considered seriously as a principal objective. It now remains to be pointed out that this oxidation, when brought about indirectly, that is, through the interaction of these elements, or certain of their compounds with oxygen bearing compounds, as is the case in this process, involves two other principles as well. These are the principles of reduction and neutralization, for it is manifestly impossible under these conditions that one substance can be oxidized without another's being reduced, and it develops, as will be shown later, that this interaction is made possible through the immediate neutralization of the oxides of these substances. While these principles and the reactions by which the purification is brought about are, when considered separately, very simple and can be easily understood, they are somewhat difficult to follow in the actual working of the furnace, because they are here occurring simultaneously and, therefore, tend to mask each other in the effects they produce. For this reason it is best to consider the subject, first, from the standpoint of the chemical properties of the elements affected and of the oxygen compounds of these elements under the conditions of the basic open hearth process.

Properties of Iron and Its Oxides: One of the most marked of the chemical properties of metallic iron is its tendency to combine with oxygen. Even at ordinary temperatures this tendency is very marked, as is seen from the ease and quickness with which it combines with oxygen and water to form the familiar compounds known commonly as iron rust. These compounds are but the hydrated sesqui-oxide, or per-oxide, of iron containing varying amounts of combined water, as represented by the formula $Fe_2O_3.xH_2O$. This tendency of iron and oxygen to combine becomes stronger as the temperature rises, so that at a temperature ranging from 800° to 900° C., or higher, the combination becomes very rapid, and a compound quite different from those composing rust is formed. It is commonly known as **Scale,** and is represented by the formula Fe_3O_4, or $FeO.Fe_2O_3$. These facts help to explain why iron is seldom found in nature uncombined, and the two compounds represented by the formulas given above, together with the carbonate of iron, constitute the valuable part of all the ores of iron. The ore used in most of our furnaces is the red hematite, which for the purpose of this discussion, may be considered as being composed of the sesqui-oxide, Fe_2O_3, and gangue. Besides free oxygen, certain compounds may, at high temperature, serve as sources of supply of oxygen to iron. Among these are carbon dioxide and water vapor, which constitute the chief products of combustion in any case of burning a fuel in the presence of an excess of oxygen, such as normally exists in an open hearth furnace. The heating of free iron to these high temperatures in contact with either free oxygen or steam always results in the formation of Fe_3O_4, according to the following reactions:—$3Fe+2O_2=Fe_3O_4$, $3Fe+4H_2O=Fe_3O_4+4H_2$. But at a temperature of 1000° C. or more, with iron in contact with carbon dioxide, another and less com-

mon oxide, FeO, is formed, thus: $Fe+CO_2=FeO+CO$. Ferrous oxide, FeO, and ferroso-ferric oxide, Fe_3O_4, may be formed in the furnace in other ways, also, one of which is by the progressive reduction of Fe_2O_3. If Fe_2O_3 be heated to a high temperature it loses oxygen and is converted into Fe_3O_4. This change takes place at temperatures between 1100° and 1200° C., some 500 degrees below the maximum temperatures of the open hearth. If FeO be formed under conditions even only slightly oxidizing, it passes into Fe_3O_4. Another difference in the properties of these oxides, which is of great importance in considering the chemistry of the open hearth, is seen in their power to neutralize acids. Thus, while both Fe_2O_3 and FeO exhibit very marked basic properties and combine rapidly with acid oxides, Fe_3O_4 cannot be induced to form corresponding salts at the temperatures that prevail in the open hearth. Pure scale, Fe_3O_4, fuses at about 1450° C., a temperature easily attainable in the open hearth, and it dissolves readily in either iron or calcium silicates. Ferrous oxide, FeO, is soluble in both the molten iron and the slag, and though the amount that remains dissolved in the metal when solid is small, being seldom present to an extent greater than .315 per cent. the equivalent of .07 per cent. oxygen, its effects are very harmful, as it produces both red and cold shortness in the metal. With metallic manganese it gives the following reaction: $FeO+Mn=Fe+MnO$. MnO is not soluble in the molten metal, which fact assists in accounting for the efficiency of manganese as a deoxidizing agent.

The Importance of Ferrous Oxide, FeO, in the Part Played by the Oxides of Iron in the Process: From what has been said concerning the properties of the three oxides of iron, it is evident that ferrous oxide, FeO, is the principal, perhaps the only, direct oxidizing agent in the open hearth process. Although iron sesquioxide, Fe_2O_3, may be charged into the furnace, much of this oxide is transformed by the heat into ferroso-ferric oxide, Fe_3O_4, before it has an opportunity to become active. Besides, since the impurities are held in solution by the metal, either the oxidizing agent must dissolve in the metal, a condition that is not true for either Fe_3O_4 or Fe_2O_3, or the oxidation of the impurities must occur at the surface of contact between metal and slag. That conditions in the open hearth during the melting period tend to form an abundant supply of ferrous oxide can be shown by an analysis of the first slag formed, as is illustrated by the following analyses of samples of this slag taken just before the introduction of the hot metal.

Table 40. Analysis of First Slag Formed in Basic Open Hearth Heats

	SiO_2 %	FeO %	Fe_2O_3 %	MnO %	P_2O_5 %	Al_2O_3 %	CaO %	MgO %	S ($S+SO_3$) %
Slag from Fce., No. 9.....	8.54	61.05	11.10	2.31	.26	1.98	9.13	5.48	.16
Slag from Fce., No. 15.....	1.00	78.24	15.31	.81	.14	.37	2.70	1.12	.25

Concerning the neutralizing powers of these oxides, FeO must also act as the initial base, as will be shown later, but in the slag Fe_2O_3 is also capable of acting as a base. It is important to emphasize these facts here because of their influence on the chemical action of the other elements eliminated during the purification period, for their action depends on the conditions, which it is, therefore, essential to define. Briefly, the chief of these conditions is that at the time of introducing the hot metal there is present in the furnace a slag that is very rich in ferrous oxide.

Properties of Silicon and Its Oxide, Silica: Silicon forms but one compound with oxygen under the conditions prevailing in the open hearth, and this compound is silica, SiO_2. The tendency of silicon to combine with oxygen is even stronger than that of iron, due to the greater heat of formation of its oxide, so that it is capable of reducing any of the oxides of the latter, and upon this fact depends the elimination of this element from the molten metal. As to which of the oxides of iron is the active agent in the oxidation of silicon, there can be little doubt but that ferrous oxide, FeO, is the principal one that suffers direct reduction by the silicon, for, as already indicated, the silicon, either in elementary form or as a compound of iron, is distributed throughout the mass of molten metal, and it is necessary that either the oxidizing agent also dissolve in the liquid or the silicon diffuse to the surface of the metal in order that the molecules may be brought into that intimate contact required to effect a reaction. The oxidation of the silicon, then, is represented by the following reaction: $Si+2FeO=SiO_2+2Fe$. Silicon, however, is a very strong acid, so that if this reaction occurs, the silica will immediately combine with ferrous oxide to form a bisilicate, a tri-silicate or some still more acid salt, depending upon the relative amount of base available. Since this reaction takes place with only a limited supply of ferrous oxide present, it may be assumed that the salt requiring the least base, such as the tri-silicate, would be formed. If so, the reaction would be as follows: $3\ SiO_2+2FeO=(FeO)_2\cdot(SiO_2)_3$. If the bisilicate is formed, the reaction would be represented thus: $SiO_2+FeO=FeO\cdot SiO_2$. Since the neutralizing action must always instantly follow the formation of SiO_2, it is perhaps best to represent the change by a single reaction, which can be done by combining the first two, thus: $3Si+8FeO=(FeO)_2\cdot(SiO_2)_3+6Fe$. The ferrous silicate is in the fluid state, for its fusion point is below that of the metal. It is of lower density than the iron, and, therefore, rises to the surface, where it temporarily forms a part of the slag. On the way to the slag it may undergo a change as noted later under manganese. Once in the slag, this ferrous silicate is capable of undergoing many changes. The first of these changes is probably due to the ability of the silica to take on additional base. Having been formed in a region where there is only a limited supply of base, the silica could not be neutralized to the extent it is capable. But now, having diffused into the slag, where there is abundance of bases, this trisilicate may become a monosilicate with either a monoxide or a sesqui-

oxide base. The formation of the monosilicate with the monoxide base, FeO, may be represented thus: $(FeO)_2 \cdot (SiO_2)_3 + 4\ FeO = 3(FeO)_2 \cdot SiO_2$. The ferrous oxide thus combined cannot act as an oxidizer and, therefore, becomes inactive. However, it may be made available through the action of lime and magnesia. Both these bases are capable of replacing ferrous oxide in the manner indicated by the following reactions:—

$$(FeO)_2 \cdot SiO_2 + \begin{cases} 2\ CaO \\ 2\ MgO \end{cases} = \begin{cases} (CaO)_2 \cdot SiO_2 \\ (MgO)_2 \cdot SiO_2 \end{cases} + 2\ FeO.$$

The ferrous oxide thus liberated is now subject to reduction, and available to the bath for further use. The sources of supply of lime and magnesia are the stone charged into the furnace and the lining of the furnace itself. These alkaline earth silicates constitute the major portion of all the final slags formed in the process, but these slags are never free of iron, for they hold its oxides in solution.

Properties of Manganese and Its Oxides: While manganese combines with oxygen in several different proportions to form an equal number of different oxides, under the conditions that exist in the basic open hearth only one of these oxides is formed, namely, the manganous oxide, or protoxide of manganese, MnO. Like silicon, the manganese in the charge, being alloyed with iron, must be oxidized largely through the agency of ferrous oxide. But as silicon is capable of reducing manganese oxide, there appears little chance of oxidizing the latter until the former element has been largely eliminated from the bath. However, there is much evidence to show that at least a part of the manganese finds its way into the slag long before all the silicon has been oxidized. This fact is explained by the assumption that manganese is capable of replacing iron in the silicates of iron, thus: $FeO \cdot SiO_2 + Mn = MnO \cdot SiO_2 + Fe$. or $(FeO)_2 \cdot (SiO_2)_3 + 2Mn = (MnO)_2 \cdot (SiO_2)_3 + 2Fe$. With this idea in mind, it is easy to conceive the simultaneous elimination of both these elements, in which elimination the ferrous oxide plays the part of oxidizing agent, only, and manganese fulfills the office of the base for the neutralization of the silica. Such a change, involving the simultaneous oxidation of silicon and manganese, is represented by the following reaction: $3\ FeO + Si + Mn = MnO \cdot SiO_2 + 3Fe$. When this silicate of manganese reaches the slag, it is subject to the same changes as are the corresponding iron oxide silicates, the manganese oxide being eventually set free by lime and magnesia. This free oxide of manganese, being insoluble in the metal, remains in the slag as such as long as the latter is rich in iron oxides; but if the slag should be depleted of its oxides, then manganous oxide is liable to reduction, in which event the resulting metallic manganese returns to the bath. Another property of manganese, though it is of little importance in ordinary open hearth operations, may be mentioned. It refers to the ability of manganese to replace iron in combination with sulphur. Thus, all the sulphur contained in the cold pig iron and steel scrap going into the furnace may be considered as being combined with this element and in the form of manganese sulphide. This

substance is slightly soluble in the slag as well as in the metal, and this fact accounts for the presence of small amounts of sulphide found in open hearth slags. On the surface of the slag, in contact with an oxidizing flame, manganese sulphide is subject to oxidation according to this reaction: $2MnS+3O_2=2MnO+2\ SO_2$. The sulphur dioxide, SO_2, thus formed is a gas and may escape from the furnace with the products of combustion. However, it is evident that the quantity of sulphur removed in this way must be very small.

Sulphur and Its Oxides: Owing to the peculiar properties of sulphur and its oxides, they are subject to a number of conflicting influences, under the conditions of the open hearth process, that render the removal of this element very uncertain. As an element, sulphur combines directly with iron to form iron sulphide and is easily oxidized to form oxides, SO_2 and SO_3, both of which are gaseous acid anhydrides, and, when neutralized, form sulphites and sulphates, respectively. At temperatures far below the lowest working temperature of the open hearth, the sulphites and sulphates of the heavier metals, like iron, for example, decompose to form either the sulphide or the oxide of the metal and sulphur dioxide. At temperatures relatively low for furnace operations, like that of the puddling furnace, both manganese and iron sulphides may react with the higher oxides of these elements, such as Fe_2O_3, forming oxides of the metals and SO_2, which escapes, as a gas, from the furnace. At the higher temperatures of the open hearth there are a number of factors that operate against the elimination of the sulphur in this way, among which may be mentioned an increased tendency of iron to combine with sulphur, an increase in the reducing power of the molten iron, the fact that CO gas is capable of reducing SO_2, and the probability that there is little Fe_2O_3 available to do the work. Fe_3O_4 may replace Fe_2O_3 in the oxidation, but it is very improbable that FeO is capable of producing the same result. Unlike the sulphates of the heavy metals, the sulphates of the alkaline earths, such as calcium sulphate, $CaSO_4$, are not so readily decomposed by heat alone, though at the higher temperatures of the open hearth $CaSO_4$ will give off some of its sulphur. Therefore, once the sulphur is oxidized and thus combined with lime, there is some chance of its being held by the slag. However, iron is capable of decomposing the sulphate of lime, thus, $CaSO_4+4\ Fe=FeS+CaO+3\ FeO$, in which case the iron sulphide dissolves in the iron. As evidence that such a reaction may take place, several instances may be cited in which steel has been ruined, for the order it was intended, through charging old boiler tubes, containing much boiler scale, with the scrap. The presence of oxides in the slag tend to hold this reaction in check, so that it takes place to an appreciable degree only when the slag is burdened with an excessive amount of this sulphate, and even then it can occur only at the surfaces of contact between metal and slag.

Sulphur From the Fuel: Another source from which sulphur may be imparted to the metal is the fuel. That fuel carrying compounds of sulphur

may be responsible for a portion of the sulphur content of steel is a well known fact, but through what reactions the transfer is brought about does not appear to have been satisfactorily explained. Now, it has been established by J. B. Ferguson, writing in the Journal of the American Chemical Society, November, 1918, that "CO and SO_2 react between 1000°C. and 1200°C. to form CO_2 and sulphur vapor and traces of carbon oxysulfide in mixtures rich in CO." In the early stages of an open hearth heat, just after the addition of the molten pig of the charge, these conditions as to temperature and presence of CO gas prevail at the surface of the charge, and any sulphur vapor that may be formed as above will readily be taken up by the exposed molten or solid metal of the charge, forming iron sulfide. If there is taken into account the action of manganese toward sulphur, there are, then, two agencies that act feebly to eliminate sulphur from the metal, and two that are active, also feebly, in returning it, or of introducing it. The stability of the calcium sulphate, however, acts as a guard against the introduction of the element, except under some such unusual condition as that noted above.

Phosphorus and Its Oxides: This element is very easily oxidized, when in the free state, by oxygen alone, and forms several oxides, of which only one, phosphorus pentoxide, P_2O_5, need be considered here, because it is the only one formed under the conditions prevailing in the open hearth. Like sulphur, phosphorus occurs in the metal as a definite compound, iron phosphide, Fe_3P, and like silica, the oxide, P_2O_5, is an acid, which must be neutralized as soon as it is formed. The reaction by which it is removed from the metal is, therefore, probably most nearly correctly represented by the following expression: $2\ Fe_3P+8FeO=(FeO)_3\cdot P_2O_5+11Fe$. Silica has the power of replacing P_2O_5 in the ferrous phosphate, thus exposing the latter oxide to reduction, so that phosphorus is never permanently removed from the metal until the silicon has been practically all eliminated. This power of silica also accounts in part for the fact that phosphorus is not eliminated by any of the acid processes for making steel, for the proportion of this compound in the slag effectually prevents the formation of the phosphate. In the basic process the abundance of bases present in the slag is more than sufficient to satisfy the silica, so that the ferrous phosphate is not only permitted to form, but on reaching the slag it is converted into a much more stable calcium phosphate, probably the tri-calcium phosphate, $(CaO)_3\cdot P_2O_5$. Even this salt is, relatively speaking, easily reduced. Phosphorus, therefore, is held by the slag only so long as the latter is maintained strongly basic and at least moderately oxidizing.

Carbon and Its Oxides: Owing to the peculiar chemical and physical properties of carbon and its oxides, the elimination of this element gives rise to phenomena distinctively different from those of the elements just reviewed. In that review it was pointed out that the oxidation of those elements gives compounds which are liquids under the conditions of the open hearth, that is, they are slag forming elements. But the oxidation of the carbon, which is represented by the reactions $C+FeO=CO+Fe$ and

$Fe_3C+FeO=CO+4$ Fe, gives rise to the gas carbon monoxide, and, owing to the conditions under which it takes place, produces the phenomenon known as the ore boil. Thus, since the carbon, either as a compound or as an element, is dissolved in the metal, and the iron oxides, in the slag, the region of greatest activity, at the beginning of the oxidation, is located near the surface of contact between the two liquids. The generation of the carbon monoxide here gives rise to innumerable tiny bubbles of the gas, which immediately rise into the slag; but owing to the small size of the former and the viscosity of the latter, their immediate escape is hindered, so that they find their way to the surface very slowly. They thus collect in the slag, increasing its volume and imparting to it the appearance of foam. In the course of time, the highly oxidizing condition of the bath has disappeared with the consequent lowering of the carbon content, and both oxide and carbon are so reduced in amount that the oxidation no longer takes place rapidly and near the surface of the metal; so the slag loses the foamy appearance. Indeed, as the silicon, manganese, phosphorus and part of the carbon have been oxidized, the bath of metal is becoming depleted of its reducing agents, so that more and more ferrous oxide penetrates or is dissolved by the metal, which fact, together with the decomposition of the limestone, gives rise to the formation of large bodies, or bubbles, of carbon monoxide deep down in or near the bottom of the layer of metal. These bubbles rise through the metal rapidly, so that when they strike the slag, it is not given time to part, but is lifted into the atmosphere of the furnace and thrown to one side.

The Action of the Limestone: It is interesting to note to what extent the decomposition of the limestone on the bottom of the furnace may contribute to this action and to the elimination of the carbon. The reaction representing this decomposition is $CaCO_3=CaO+CO_2$. Now, the carbon dioxide gas is no sooner set free than it is attacked by iron, thus: $CO_2+Fe=FeO+CO$. The FeO is then available for the oxidation of the carbon in the metal, thus: $FeO+C=Fe+CO$. By combining these two reactions it will be observed that, from each and every volume of carbon dioxide, CO_2, liberated, two volumes of carbon monoxide, CO, result. The CO derived from the decomposition of the limestone, as well as that from the action of dissolved FeO, escapes to the surface as just described. Any ore that might have remained at the bottom of the furnace up to this period of the carbon elimination would also contribute to the violence of this action. At the surface of the slag the carbon monoxide discharged by the bath may burn to carbon dioxide, which escapes with the products of combustion from the flame. The boiling of the bath thus plays a very important part in the process. When the slag is thrown aside by the bubbles of gas, the metal is exposed to the action of the flame, and though this exposure is but momentary in each instance, the large number of such exposures result in the formation of a considerable quantity of ferrous oxide in this way. But the greatest benefits are derived from the agitation of

the bath. It is easily seen how this agitation must result in a mixing of the slag and metal, thus increasing the area of the reacting surfaces, while the stirring effect on the metal itself should not be overlooked. Thus, the metal lying near the bottom, which is the coldest and most impure, is brought upward to be heated and exposed to the oxidizing influences, so than both the temperature and composition of the bath are kept more uniform than they could otherwise be maintained.

Effect of Carbon Elimination on Slag Composition: In conclusion it should be pointed out that the effect of the carbon elimination upon the slag is to reduce its content of iron oxides. By proper regulation of the conditions this reduction of the oxides in the slag may be brought down to the point where the total iron content of the slag will be about 10 per cent. of its weight, of which iron about 7/10, or 70 per cent., will be in the ferrous condition. The advantages of adding ore to the charge, as may now be readily seen, are to increase the speed of the purification and to decrease the waste of metal, which is more expensive than ore.

The Order of Elimination of the elements just reviewed, with the exception of sulphur, is the same as the order in which they have been discussed, namely, silicon and manganese, phosphorus, and lastly carbon. Some reasons why the first three elements are eliminated in this order have been mentioned under their respective headings, but nothing has been mentioned that would appear to cause carbon, which is capable, under proper conditions, of reducing the compounds of all these elements, to be the last element oxidized in the open hearth. The explanation for this difference in the chemical properties of carbon is connected with the fact that its reducing power increases as the temperature rises. Again, chemical action, when it occurs independently of external influences, always takes place in the direction that will liberate the most energy, as was pointed out in Chapters I and IX. The oxidation of silicon, manganese, and phosphorus and the neutralization of the resulting oxides are exothermic reactions, whereas the carbon reaction is endothermic. The elimination of the four impurities thus takes place in accordance with the amounts of heat evolved or absorbed. As an example of these laws, let the elimination of silicon and carbon be compared. These reactions with the heat, or energy, values involved, are as indicated in the following expressions:

(1) $Si+2\,Fe\,O = SiO_2+2Fe(+64600\text{ cal.})$
$-2(65700)\ +196000=64600$

(2) $C+FeO=CO+Fe\ (-36540\text{ cal.})$
$-65700+29160=-36540$

Reaction (1) shows that in the oxidation of one gram of silicon approximately 2307 cals. ($64{,}600\div 28=2{,}307$) of heat are evolved, while in the oxidation of one gram carbon, as shown by reaction (2) 3,045 cal. of heat are absorbed. If now the reduction of silica and carbon monoxide by carbon and silicon, respectively, be compared as in reaction (3) and (4), it will

be seen that, whereas carbon absorbs heat in reducing silica, silicon reducing CO, liberates heat.

(3) $SiO_2+2C=2CO+Si(-137640cal.)$ (4) $2CO+Si=SiO_2+2C(+137640cal.)$
$-196000 \quad +2x29160$ $-2x29160 \quad +196000$

It is evident, then, that the oxidation of the carbon cannot be complete until the silicon has been eliminated. At high temperatures, such as may prevail in parts of the blast furnace or in the electric furnace, for example, the heat absorbed in reaction (3) is supplied from external sources, which addition of energy causes the carbon to act as a reducing agent toward the silica. What has been said with respect to silicon also holds true in the case of manganese and phosphorus. In the basic open hearth the temperature rises gradually, so that carbon has no opportunity to act as a reducing agent toward oxides of these elements.

Factors Opposing this Order of Elimination: What has been written above should not be taken to mean that each element is completely and successively eliminated in the order mentioned, for there are other laws, such as the law of mass action, for example, that operate to bring about the elimination of these elements simultaneously. The oxidation of the carbon, for example, evidently begins shortly after the hot metal has been added to the charge, and certainly before the manganese and phosphorus have been entirely disposed of. What is implied is that the elimination of each element in the order named is successively in the ascendency until eventually only the carbon, in part, remains to be oxidized. When this element has been practically all removed, the bath of metal no longer contains reducing agents and is subject to over-oxidation by absorption of ferrous oxide, FeO, up to the point of saturation in equilibrium with the slag. This fact explains why it is undesirable to make ore additions to the slag just previous to tapping, and also why the heat, unless deoxidizing agents are added to the bath, should not be held in the furnace for more than a few minutes after the carbon content has been lowered to .10 per cent., which figure is within about .03 per cent. of the minimum carbon content for this process.

Resumé: All that should now be required in order that the chemistry of this process may be fixed clearly in mind, is a rapid review of the subject matter included under the heading of Operation of the Furnace, which will now appear in a new light. To begin this review, picture a furnace in the course of operation which has received its charge of solid materials for, say, a Monell heat. The first effect on this charge will be an increase of temperature. The limestone, ore and the lining of the furnace, all being basic in character, will remain inactive at first, and continue so until they will have absorbed sufficient heat to raise their temperature to the point where decomposition begins. For limestone this temperature is about 850° C., while the ore will not give up its oxygen until its temperature is near the fusion point, about 1400° C., unless it comes in contact with reducing agents. The absorption of heat by the ore and stone is hindered by the

scrap charged upon them. This material, being a good conductor of heat and exposed to the flame, absorbs heat very rapidly, and as soon as the temperature rises above the thermo-critical range, oxidation of the iron begins, this giving rise to the formation of scale. The melting point of this scale is so near that of the metal, that it may remain on the surface until the metal itself begins to melt. It is understood, of course, that the impurities contained in the scrap will suffer oxidation with the iron. These fluids will trickle down over the colder material beneath and will eventually reach the ore on the bottom of the furnace. Here, together with additional oxide derived from the ore and some silica, lime, etc., collected from various sources, this molten scale will go to make up the first slag. This slag, poor in silica, but exceedingly rich in iron oxides, especially ferrous oxide, and containing some lime also, is well constituted for the work it has to do; and with the addition of the hot metal, the purification may begin at once. Thus, the silicon, manganese and phosphorus will have been practically eliminated from the metal within two hours after the molten metal is charged. The extent and character of the purification of the metal at the time of the run off with the resulting change in the composition of the slag are indicated in the following table of analyses.

Table 41. Analyses of Hot Metal and Slag Before Charging and at Time of First Run-off.

		ANALYSIS OF METAL. Per cent. of					PARTIAL ANALYSIS OF SLAG. Per cent. of								
Heat No.		C	Mn	P	S	Si	SiO_2	FeO	Fe_2O_3	MnO	CaO	MgO	P_2O_5	SO_3	S
1	Pig Iron Before Charging	3.85	1.55	.198	.035	1.04	4.72	66.67	not det'md	1.30	18.00	2.00	.78	....	....
1	At Time of Run Off	2.39	.05	.022	.040	.04	19.19	32.86	5.22	12.97	18.38	6.11	1.11	....	....
2	" " " " "	2.41	.02	.053	.060	....	25.18	17.39	4.07	13.16	17.88	12.18	.....	.090	.029
3	" " " " "	2.45	.02	.068	.049	....	23.68	26.33	7.10	13.54	12.22	10.14	.....	.090	.027
4	" " " " "	2.80	.01	.015	.043	....	15.74	45.16	7.50	6.19	11.34	5.23	.....	.165	.037
5	Briquettes Instead of Ore Used	3.74	.01	.043	.037	....	19.30	42.59	5.91	6.84	12.41	3.84	.....	.182	.063

From this point the reader should be able to continue this review through the oxidation of the carbon unaided, and in doing so, he will have fixed in mind the chemistry of the process much more firmly than if he but read the inadequately expressed thoughts of another. As a further aid, what is said in Chapter V concerning final open hearth slags should be referred to.

SECTION VIII.

OPERATION OF THE ACID OPEN HEARTH.

Introductory Remarks: The number of workmen required to operate an acid open hearth is the same as for the basic process, and, in a general way, their duties are the same. If there is any difference, the manual labor about the acid furnace may be somewhat heavier than on the basic, as nearly all ore charging in the former process must be done by hand. The drying and heating of the acid furnace is also conducted in the same manner as for the basic furnace. Before the furnace is heated too hot, however, the tapping hole must be put in shape.

Preparation of the Tapping Hole: In most furnaces the opening left in the brick work for a tapping hole is square in section except at the top, which is arched. This opening, measuring about 16 inches across, must be lined with some acid refractory material that will set hard and resist the eroding effect of the liquid metal and slag. To form this lining a taper plug of iron or wood, varying in size from 4 to 10 inches in diameter, according to the size of the furnace, is inserted centrally into this hole in the brick work, and the space between the plug and brick is rammed full of ground ganister containing a little plastic clay as a binder. When this mixture has set, the plug is removed, and the round opening is filled with anthracite coal, which is immediately covered on the inside of the furnace with a little sand, so the coal will not be burned out during the heating of the furnace. Outside, the coal is held in place with a plug of fire clay. Some melters prefer to tamp the hole full of ganister and then dig out with a sharp, curved spoon some of this filling to form a small cylindrical shaped hole, which is left open until after the bottom and banks have been fritted in. This hole is then stopped about as described above.

Making Bottom: After the tapping hole has been made ready, the heating of the furnace is carried on as described under the basic process. In the meantime, preparations are made for fritting or glazing on the sand bottom and banks. As a first step, enough sandstone or granite chippings, if such chippings are procurable, are scattered over the bottom and banks to cover the surface. Then, as soon as the furnace has come to a red heat, more gas is admitted and the valves are reversed at about twenty minute intervals until these chippings begin to fuse. This procedure permits the bricks in the banks and bottom to absorb more heat then if the sand is spread directly upon them, and the partly fused chippings form a better bond between the almost infusible silica brick and the sand fritting. By means of shovels, rabbles, and long handled spoons, silica sand is now spread evenly over the surface of the bottom and banks to a depth of about ¼ inch, and the heating is continued until this sand begins to fuse, thus forming a glaze over the entire surface.

Another layer of sand is then spread and glazed on as before, and these operations are repeated until the bottom and banks have been built up to the desired thickness, which varies, according to the size of the furnace, from 12 to 20 inches. The bottom may now be compared to a big oval dish, the semi-vitrified layers of sand forming practically a solid one-piece wall about the sides and bottom.

The Quality of the Sand Used for this purpose is of very great importance. If the sand is very pure, that is, composed almost entirely of silica, great difficulty is experienced in fritting it on the bottom, while if it contains too high a percentage of impurities, it will be easily fritted, but will also be rapidly worn away after the furnace is put into operation. The silica content of the sands, or sand mixtures, that give the best results is usually between 94 and 97 per cent. No definite figures can be given as an analysis of a good sand, because the adaptability of the sand for this purpose depends not only upon the kind and relative amounts of impurities present, but also upon the physical make-up of the sand itself. Certain natural sands, including some beach sands and a few deposits in Ohio and other mid-western states, give the best results. In Western Pennsylvania, some of the most desirable material occurs as hard sedimentary rock, which has to be crushed to render it suitable for this purpose. In fineness, this stone is crushed so that all will pass a ¼-inch screen. Frequently a relatively coarse and pure sand mixed intimately with a certain proportion of a fine and less pure sand will give good service as bottom material, even when either sand alone has proved unsatisfactory. The following table of analyses has been found helpful in the selection of suitable sands for this purpose.

Table 42. Showing Chemical Analyses of Different Sands Used for Acid Open Hearth Bottoms and Banks.

GRADE	Good	Bad	Fair	Fair	Good	Mix*	Mix*
Composition	%	%	%	%	%	%	%
Silica, SiO_2	95.83	88.46	97.38	95.01	96.34	98.45	92.36
Iron Oxide, FeO	.40	.96	.45	.51	1.05	.13	2.90
Alumina, Al_2O_3	2.76	8.27	1.48	3.44	1.60	.85	2.85
Lime, CaO	Trace	Trace	Trace	.10	.21	Trace	Trace
Magnesia, MgO	.13	.23	.08	Trace	.21	Trace	Trace
Alkalies, K_2O+Na_2O	None	None	Trace	Trace	None	Trace	Trace
Ignition Loss	.88	2.08	.64	1.05	.62	.52	1.57

*These two sands may be mixed in about equal proportions.

First Charges in a New Furnace: After the bottom and banks have been properly fritted, or glazed in, the tapping hole is punched through from the outside and again made up as before, using a mixture of anthracite coal and sand and securing this in place with a plug of fire clay rammed in from the outside. The hearth is then filled nearly half full of acid open hearth cinder. If the cinder is not at hand, red brick bats or other easily fused silicious material is substituted, and some light scrap, such as sheet trimmings, is scattered on top. When this charge has melted, rabbles are inserted through the doors and the liquid slag is splashed up against the banks to wash them down. Then the bottom, itself, is carefully raked over to smooth it, after which the tapping hole is opened and the slag is drained out of the furnace. This treatment tends to consolidate the bottom and banks and make them much more resistant to the buoyant action of the liquid metal of subsequent charges. The next two or three charges will be small, not over two-thirds the capacity of the furnace, and will consist mainly of cold pig iron. Then, if it is apparent that the bottom is holding well, the size of the charge and the proportion of scrap used may be gradually increased until the furnace is working on its normal charges.

Materials for the Charge: In acid open hearth practice, the initial charge consists normally of cold pig iron, or cold pig iron and scrap. No ore can be added with the charge as in the basic process, for the iron oxide, being a base, would combine with the acid lining and rapidly destroy the bottom and banks. For the same reason the melting of scrap alone would be bad practice. Hence, the use of hot metal, molten pig iron, to supply the whole of the pig iron part of the charge is impracticable.

The Proportion of Scrap to Pig Iron may vary over wide limits. As previously pointed out, Siemens originally used no scrap, and as ore was added to the pig iron after melting to hasten the oxidation of the metalloids, his process was called the pig and ore process. Later, the Martin brothers used scrap with only enough pig iron to make the carbon content of the melt that desired in the finished steel. As they used no ore, their method of working was called the pig and scrap process. The modern method, in which a charge of pig and scrap is melted, then ored down or pigged up as required, may be looked upon as a combination of these two methods. In it, the relative amounts of pig iron and scrap in the charge are largely controlled by plant and market conditions, that is, the supply and relative cost of these materials. If both are available, then the only thing considered in proportioning the charge is the carbon content it is desired the charge should have when melted.

Grade of Scrap and Iron for the Charge: Only a trace of the phosphorus and none of the sulphur is eliminated in the acid open hearth process. Indeed, the finished steel may contain a slightly higher percentage of both of these elements than the average of the charge. This

increase is due to the fact that, while the weights of the sulphur and phosphorus remain practically constant, the weight of the metal may, owing to losses through oxidation of iron and metalloids, be considerably decreased. In addition, the bath is liable to absorb some sulphur from the flame. Consequently, great care must be exercised to see that the average sulphur and phosphorus content of the charge is somewhat below that required in the finished steel. Silicon, manganese, and carbon are very readily oxidized in this process, so require less consideration in the selection of materials. The specifications for acid open hearth pig iron usually require a silicon content under 2.00 per cent., manganese 1.00 to 2.00 per cent., and phosphorus and sulphur under .03 per cent. To produce the best grades of steel the average manganese content of the charge should be 1.50 to 1.75 per cent. In steel for common grades of sheets the phosphorus content may be somewhat higher, under .06 per cent. being satisfactory. It is an easy matter, either at the blast furnaces or at the steel works, to secure a representative sample of any lot of pig iron, and its selection offers little difficulty. But it is almost impossible to secure a representative sample of the scrap for analysis, hence the scrap must be selected by inspection, and with much care and judgment. For example, in order to produce a steel with a phosphorus and a sulphur content each under .05 per cent., such scrap as tubes, pipe, sheet, Bessemer rails, and castings must be avoided. The size of the scrap is also of some importance. Unless the proportion of pig iron is large, light scrap makes it difficult to get a full charge into the furnace. Besides, light scrap, unless extraordinary precautions are taken in charging, is excessively oxidized in melting. This oxidation of the iron not only decreases the yield, but the resulting iron oxide combines with the silicious lining and rapidly fluxes out the bottom and banks of the furnace.

Manner of Charging: A few small and isolated furnaces may be still charged by hand, but in the main all the larger furnaces will be charged by machine. As to the order in which the pig iron and scrap is charged, it is unimportant which is charged first, if the scrap is heavy or makes up less than half of the total charge. But if the scrap is light, many prefer to charge it ahead of the pig iron, which, being spread out on the top, tends to shield the scrap from direct contact with the flame and to prevent its being excessively oxidized. Others make a practice of charging part of the pig iron on the bottom and part on top of the scrap. The pig iron on top melts first, and, trickling down over the scrap beneath, the silicon and carbon it contains react with iron and manganese oxides as soon as formed, thus insuring that the latter do not come in contact with the bottom or banks. The added protection afforded by a little pig iron on the bottom is obvious, and is a great advantage. It will not only increase the yield but will also save much repairing of the bottom. As soon as the liquid basic oxides of iron and manganese come in contact with the acid oxides of silicon in the lining, silicates of these

oxides are formed and become slag. Then, not only are the banks rapidly eroded away, but the iron and manganese oxides are neutralized and have lost their power of oxidizing and neutralizing the metalloids in the pig iron.

Melting: As soon as the furnace has been charged, the gas, which is usually partly turned off during the charging, is turned on full, and the flame is reversed every 10 or 15 minutes in order to step-up the temperature and melt down the charge as quickly as possible. The heat usually requires little attention during the first part of this period, so the time is generally occupied in preparations for the tapping. The steel ladle requires a new nozzle and a new stopper, and the ladle and cinder pits must be cleaned out,—duties performed by men on the pouring floor. On the charging floor, the second helper cleans and repairs the steel runner, sets it in place, and sees that it is thoroughly dried, procures, or has brought to the furnace, the ferro-manganese, ferro-silicon, anthracite coal, and other deoxidizers and recarburizers required. Advantage of this time will also be taken to clean up about the furnace. From four to five hours time is required to melt the charge. Toward the end of this period, the first helper, or melter, will keep a close watch upon the action of the heat. If the charge contained a larger proportion—over half—of pig iron, especially if the iron carries a high silicon and low manganese content, the slag formed will be very thick or viscous, and, in order to hasten the process and increase the yield, it is necessary to add a little ore, or lime. Great care must be used in adding lime, else the banks will be destroyed. On the other hand, if the charge was composed chiefly of scrap, or the pig contained a low percentage of silicon, it may be advisable, in order to save the banks and bottoms from excessive scorification, to add some sand, old brick, or other silicious material.

Adjusting Conditions After Melting: After the charge has completely melted, the metal should, and usually does if the heat has been handled right, contain from 30 to 60 points (hundredths of a per cent.) more carbon than is required in the finished steel. Some melters prefer to have the heat melt with a carbon content of more than one per cent. in all cases, but for soft steels this practice will not improve the steel and may cause additional labor. Unless the charge was made up largely of a high silicon pig iron and the heat was not given proper attention near the end of the melting period, practically all of the silicon and manganese will have been oxidized and neutralized, forming the slag. This slag is normally made up of about 50 per cent. of bases, principally iron and manganese oxides, and 50 per cent. acids, or silica. With its acid and bases in these proportions it is practically neutral, or in a state of most stable equilibrium, and has little power to act either as an oxidizing or a neutralizing agent. Moreover, this slag is self-adjusting, so that, if the acids be increased, the slag will tend to retard the elimination of silicon and carbon from the metal, and, if the bases be increased, it will

hurry the elimination of these elements. But if the bases are increased too much the slag will absorb silica from the banks. This knowledge is of considerable importance in the subsequent handling of the heat, but the ability to recognize these slag conditions is acquired only by close observation and experience.

Working the Heat: The problem now before the melter is to reduce the carbon content as rapidly as possible and at the same time get the metal heated up to a temperature that will permit the heat to be tapped and teemed satisfactorily. In order to determine the carbon content of the bath, a fracture test of the metal may be taken in the manner already described under the basic process, but experienced melters are able to estimate the carbon content fairly well from the nature of the boil on adding ore. If the carbon is still relatively high and the metal is quiet and hot enough, a few lumps of ore are added to start a boil. If the metal appears too cold, before any ore is added attempts will be made to raise its temperature by turning on more gas and reversing the flame more frequently. After this ore has had time to react with the carbon in the steel, another sample is taken. If the carbon is still too high, more ore is added, or if it has decreased a great deal, it may be necessary to add some pig iron to hold the carbon until the temperature desired for casting can be reached. Thus, by frequently sampling the metal and treating it as required, the carbon and the temperature will, in the course of 3 or 4 hours, be adjusted to points where the heat can be tapped. Low carbon heats, that is, heats with carbon under .30 per cent., will be worked down to a carbon content of .10 or .12 per cent., then tapped, and the carbon content brought to the desired point through the addition of recarburizers. This point is selected for tapping because it is easier to read the fractures and also because the carbon is oxidized very slowly under .10 per cent. and the composition of the steel is not likely to change very much, not more than a point or so, if there should be any delay in getting the heat out of the furnace. Since no phosphorus is eliminated in this process, the addition of large amounts of pig iron or spiegel for recarburizing is inadvisable, lest the phosphorus content of the steel be increased beyond the limit allowed. Therefore, medium and high carbon heats are usually caught on the way down, though if pig iron or spiegel of suitable grades are to be had, many hold that better steel can be made by working the carbon down and recarburizing with these materials in the furnace. This method cannot be used, however, if the order calls for low silicon in the steel.

SECTION IX.

FINISHING ACID OPEN HEARTH STEEL.

Finishing the Heat: During the last hour the heat is in the furnace very little ore is added, and none at all if it can be avoided, otherwise the steel will dissolve oxide and be "wild" as a result. The amount of ferrous oxide the liquid steel absorbs or dissolves varies with the amount

present in the slag for any given heat, or, in general, the concentration of ferrous oxide in the steel to the concentration of ferrous oxide in the slag is in the nature of a fixed ratio. On the other hand, if the slag is wholly depleted of excess ferrous oxide while the carbon is still being oxidized and especially if the temperature is high, as in low carbon heats, there is the danger that some of the silica may be reduced, increasing the silicon content of the steel. If the specifications permit it, the reduction of a little silica here is desirable, as it aids in deoxidizing the steel. Such a condition will be indicated by a "thickening" or increase in the viscosity of the slag, hence the melter aims to keep the slag for tapping thin or fluid. This slag is best thinned by adding a little limestone. In the following table is shown the composition of three finishing slags illustrative of the widest variations to be expected in such slags.

Table 43. Composition of Acid Open Hearth Slags.

Heat No.	PERCENT. OF						
	SiO_2	FeO	MnO	P_2O_5	Al_2O_3	CaO	MgO
8026	54.25	25.87	11.27	.045	3.28	5.37	.12
8127	52.06	20.38	20.52	.035	3.07	4.35	Trace
8340	55.60	28.90	10.23	.022	4.16	.70	.12

Finally, when the heat is thoroughly deoxidized and the temperature has been raised to the proper point and the slag put in condition for tapping, a sample of the metal is taken as before, and, if the order calls for low phosphorus and sulphur limits, it is sent to the laboratory for a preliminary analysis for these two elements. This analysis requires about 20 minutes, and during this time the carbon is held with pig iron or allowed to boil down to the point desired for tapping. If the result of the preliminary analysis is satisfactory, the heat can be tapped at once, but if the analysis shows the phosphorus and the sulphur content too high, the heat must be applied on some other order with higher limits for these elements.

Tapping: When ready, the heat is tapped by first removing from the outside the fire clay plug from the hole, with a pointed bar and a tapping hook or scraper, and then punching out and enlarging the hole from the outside with a long tapping bar inserted through the wicket of the center door of the furnace. Usually, if the hole was properly stoppered, little trouble is experienced in opening the hole in this manner, but occasionally, through accident or otherwise, some steel seeps into the hole and solidifies there. In such an event, the metal can be burned out and the hole opened in a few minutes with oxygen, a jet of which is

conducted against the red hot metal through about a 10-foot length of an eighth-inch steel pipe, bent at a right angle and connected to the oxygen tank with strong rubber hose. In former times, tap holes thus plugged with metal were very difficult to open, requiring sometimes as long as four hours to tap a heat.

Additions to the Heat: As soon as the metal is running freely from the furnace, the recarburizers and deoxidizers will be added. For plain steels these materials will consist of anthracite coal, pea size, or coke dust and ferro-manganese, with ferro-silicon if required by the order. In order to insure the uniform distribution of the manganese throughout the heat, the ferro-manganese should be crushed to pass a 1-inch screen, and should be added, preferably through a chute, by dropping it upon the stream of molten metal as it flows from the steel spout. In the case of small heats, say under 40 tons, it is advisable to heat the ferro red hot, or to add it molten. Indeed, the addition of the ferro in the molten state is to be strongly recommended in all cases. The coal or coke dust is contained in paper sacks, holding, usually, 50 pounds, so as to be easily handled and thrown into the ladle. In making alloy steels, ferro-vanadium and ferro-chromium must be added to the steel in the ladle, and preferably immediately following the manganese. Molybdenum can be obtained in several different forms and may be added to the steel either in the furnace or the ladle, but is usually added in the form of ferro-molybdenum to the steel in the ladle. Since copper and nickel are chemically negative to iron, these may be added to the steel in the furnace without loss. All the ladle additions should be made before much of the slag has flowed from the furnace. The losses in recarburizing is about the same as given for the basic process.

Teeming: The steel should be tapped at as high a temperature as possible, and, except in certain cases requiring high fluidity, as in the case of small castings, it should be teemed at as low a temperature as possible. Therefore, the metal may be allowed to cool in the ladle for 15 to 30 minutes, depending upon the size of the heat. This interval between tapping and teeming, combined with the high fluidity of the steel, gives foreign particles entrapped by the steel an opportunity to rise into the slag on the surface. Furthermore, a low teeming temperature lessens the size of the pipe and tends to inhibit segregation. The ingot moulds should be clean, uncoated, and in good condition. Washing or spraying or painting with slurries will prolong the life of the moulds, but should not be practiced, as the coatings are likely to be a source of "dirt," or non-metallic inclusions, in the steel. If the heat exhibits a tendency to be wild, a little aluminum, about 1 to 2 ozs. to the ton, may be added, with good results, to each mould. This aluminum should be added in the form of shot or small pieces. But for the finest grades of steel, such as gun forgings, the addition of aluminum is not permitted, as the products of its reactions remain diffused in the steel. Such heats must, therefore, be deoxidized

in the furnace. The sample for chemical analysis should be taken when the ladle has been half emptied of steel.

Preparation of the Furnace for the Next Charge: Efficient operation of the furnace requires that the next heat will be charged with little delay after tapping. This is possible only if the furnace is kept in good working condition from day to day and heat to heat. As soon as the heat is out of the furnace, therefore, the melter inspects the interior carefully. The steel remaining in any low places on the bottom is rabbled out and these holes are filled with bottom sand. All steel and slag is cleaned out of the tapping hole, which is then made up as at first. The proper making up of the tapping hole is very important, as any time saved by neglecting this work will likely be wasted many times in tapping the next heat. Besides, the chances of a break-out will be multiplied, and break-outs are nearly always costly and sometimes disastrous. While the tap hole is being made up, the banks are repaired by shoveling sand upon them and fritting it in place. This work requires about one hour, if the banks can be made up with one application of sand. If the banks have been badly washed out, the sand is applied in two coats and about 45 minutes are required to glaze on each coat. As soon as this work is done, the charging of the furnace should begin at once.

SECTION X.

CHEMISTRY OF THE ACID OPEN HEARTH PROCESS.

Chemistry of Melting: The elimination of the metalloids, silicon, manganese and carbon, of the charge is effected in two stages, corresponding to the melting and the boiling of the heat. Analyses show that during the melting stage nearly all of the silicon and manganese and a part of the carbon in the charge are oxidized. The only source of oxygen for this oxidation during this stage is the furnace gases, which consist of the products of combustion, mainly, nitrogen (N_2), carbon dioxide (CO_2), and water (H_2O). In addition to these, there may be present a little free oxygen (O_2) from excess air drawn into the furnace, or some carbon (C), hydrogen (H_2), and carbon monoxide (CO) from incomplete combustion of the fuel. Oxygen in excess would make the furnace atmosphere oxidizing, and the other gases would make it reducing in character. Of these gases carbon dioxide (CO_2), water vapor (H_2O), and oxygen (O_2), will oxidize iron at higher temperatures, rapidly at red heat, and form scale. The reactions are represented thus:—

$$CO_2 + Fe \leftrightarrows FeO + CO$$
$$H_2O + Fe \leftrightarrows FeO + H_2 \text{ or}$$
$$4H_2O + 3Fe \leftrightarrows Fe_3O_4 + 4H_2$$
$$2O_2 + 3Fe \rightarrow Fe_3O_4$$

The extent to which the first three reactions will proceed to the right will depend upon the proportion of these gases in the furnace atmosphere

and the temperature, being most active after the temperature rises above 700° C. This action is confined to the surface, and, until the fusion point is reached, the scale acts as a protective coat to the metal beneath. The metalloids in the metal thus oxidized must suffer oxidation also, but the composition of the metal beneath the coat of scale remains unchanged for a considerable period of time, at least. Because of the greater percentage of metalloids in the pig iron, the surface of the scrap will be oxidized to the greater depth. Obviously, the greater the surface exposed the more scale there will be formed, which fact explains why the loss is greater with light scrap than with heavy. When the melting point of the scale is reached, it begins to flow off, thus leaving the metal beneath exposed to further oxidation. This action applies to the scrap only, because, while the melting point of the pig iron is about the same or lower than that of the scale, the melting point of the scrap is much above that of the scale.

Purifying Reactions: The fact that the melting point of the pig iron is lower than that of the scale is a fortunate circumstance, for otherwise the scale would trickle to the bottom of the furnace and there react with the silica to form a slag. Besides scorifying the bottom, these oxides would lose their oxidizing and fluxing power, and the large proportion of metallic iron they represent would not be recoverable. With the pig iron in a molten state on the bottom of the furnace, these oxides of iron react with the metalloids, not only purifying the pig iron, but also giving up some of the iron they contain to the bath. Assuming the silicon and manganese to be in a state of atomic dispersion, this action may possibly involve all of the following reactions:

1. $Si + 2Fe_3O_4 = SiO_2 + 6FeO$
2. $Si + 2FeO = SiO_2 + 2Fe$
3. $SiO_2 + FeO = FeO{\cdot}SiO_2$
4. $3SiO_2 + 2FeO = (FeO)_2{\cdot}(SiO_2)_3$
5. $Mn + Fe_3O_4 = MnO + 3FeO$
6. $Mn + FeO = MnO + Fe$
7. $MnO + SiO_2 = MnO{\cdot}SiO_2$
8. $3Si + Mn + 8FeO = MnO{\cdot}FeO{\cdot}(SiO_2)_3 + 7Fe$

After the greater portion of the silicon and manganese has been oxidized, a small part of the phosphorus, if the temperature is low and the slag very basic, will also be oxidized, but later, when the slag has taken up more silica and the carbon reaction becomes active, the phosphorus salts may be reduced. Therefore, it is seldom that more than traces of phosphorus can be removed from the charge. Consequently, the only sure way to hold this element below the requirements in the finished steel is through careful selection of all the raw materials of the charge. The same statement also applies to sulphur, with the added caution that this element may be absorbed by the bath from the flame, as explained under the basic process.

Elimination of Carbon During Melting Period: If the melting could be effected instantaneously, very little carbon would be oxidized

until after the silicon and manganese were eliminated. But since the melting takes place gradually, a part of the pig iron, coming in contact with the highly oxidizing strongly basic slag, both in the liquid state, is almost completely purified, so that the percentage of carbon in the bath immediately after the melting of the charge is complete will be considerably lower than the average of the charge. The amount of the carbon thus oxidized cannot be predetermined and will vary with the proportion of pig and scrap in the charge; the working of the furnace, whether it is heating rapidly or slowly; the relative amounts of air and gas admitted; and a number of other incidental factors.

Chemistry of the Boil: By the time the charge has completely melted, the slag will have been almost depleted of excess oxides. If the carbon is low, the melter will first attempt to increase the temperature of the bath by increasing the fuel and reversing the flame more often, but if the carbon is high, say over 50 points above the content desired in the steel, the feeding of ore can begin as soon as the temperature is high enough. If the temperature is too low when the ore is added, its action is delayed and is too violent when it does occur; also, difficulty is experienced in getting the metal hot enough to tap. For this purpose a lump ore is used, because it has a low moisture content, is not carried into the flues and checkers by the draft, and gives a less violent boil than fine ore. Besides, since the lumps penetrate the slag layer, the action between ore and metal is more direct and can be localized near the middle of the furnace, thus protecting the banks. In the Pittsburgh district the ore preferred for this purpose is a red hematite. This ore gives up some of its oxygen rapidly at the temperature of the open hearth, forming the magnetic oxide Fe_3O_4, which quickly dissolves in the slag. The elimination of the carbon then takes place according to the following reactions:

1. $4C+Fe_3O_4=4CO+3Fe$
2. $C+FeO=CO+Fe$

The escape of the carbon monoxide gas gives the ebullient effect known as a boil. The ore is fed gradually in order to keep the boil under control and protect the banks of the furnace, for any large excess of ferrous oxide in the slag will react with the silica of the sand banks. Ferrous oxide dissolves in both the metal and the slag and the amount dissolved by the former varies with the concentration of the oxide in the latter. Owing to the injurious effect of this oxide upon the metal, therefore, the heat should be held in the furnace for 1 to 2 hours after charging the last ore. If the temperature is kept high enough, this treatment, since the slag is self adjusting in contact with the acid banks, will eventually cause a little of the silica in the slag to be reduced to silicon, which will enter the metallic bath and thus bring about the complete deoxidation of the metal.

CHAPTER XI.

MANUFACTURE OF STEEL IN ELECTRIC FURNACES.

SECTION I.

INTRODUCTORY.[1]

The Plan of Study: To understand the process of manufacturing steel by means of the electric furnace requires some knowledge of electrical phenomena. To the question as to what electricity is, no very satisfactory definition can be given. The modern idea is, that it is the fundamental of which all matter is composed, because there is evidence to indicate that electrons are but corpuscles of negative electricity, which, together with nuclei of positive electricity, go to form atoms. That it is either a form of energy or an agent for transmitting energy is evident, and the various phenomena attending it may be due to the production of strained conditions in the Ether, somewhat similar to the effect of heat upon water in the generation of steam. However, the question is of no importance except to distinguish the thing from the phenomena produced by it, which are of great importance. To those who have not been able to devote much time or study to the subject, these phenomena appear as deep mysteries and are difficult to understand. This study may, therefore, be appropriately introduced by a brief explanation, presented in as simple a manner as possible, of such of the phenomena and laws of electricity as apply to the subject of steel manufacture by this method. To be of the greatest help to those unfamiliar with electricity, it is necessary to begin with the fundamentals and build up such a structure as the limits of space and time will permit.[1]

Force, Work, Energy and Potential: In the industrial world the fundamental or prime factor is work. It is defined as the operation of overcoming resistance through space, or as the production of effects upon bodies. That which is the immediate cause of these effects is **force,** which is more accurately defined as that which causes, or tends to cause, a change in the motion of a body, in either velocity or direction. Thus, a column may exert a powerful force in supporting part of a building, because it tends to change the direction of motion the overburden would have if free to fall; but it does no work, because no effect is produced. Force is measured by the product of the mass of the body it acts upon and the acceleration (rate of change of motion) it produces. In the centimeter-gram-second (C. G. S.) system the absolute unit of measurement is the **dyne,** which is the force required to produce an acceleration of one centimeter per. sec. per. sec. in a mass of one gram. On the foot-pound-second (F. P. S.) system, the unit is the pound, which is the force exerted by gravity on a definite

[1]Students who are already familiar with the fundamentals of electricity may omit the first four sections of this Chapter and begin with Section V, page 372.

mass of matter. A similar unit on the centimeter-gram-second system is the kilogram, which is the force exerted by gravity on a mass of one kilogram. That which imparts to a body the ability to do work is energy. Both are, therefore, measured by the same unit. In the foot-pound-second system this unit is the foot-pound, or the work done by a force of one pound acting through a distance of one foot. In the centimeter-gram-second system a large unit is called the kilogram-meter, while a small unit, one dyne acting through a distance of one centimeter, is called the **erg.** The **joule,** equal to 10,000,000 ergs, is a more practical unit. Thus, if a weight of 10 lbs. is lifted against gravity to a distance of 5 ft., 50 foot-pounds of work has been done on that body, and 50 foot-pounds of energy was expended, and the same amount of energy is stored up in the body raised in the form of potential energy, which imparts to this body the ability to do work. In practice the body lifted would be said to have its potential raised, or a difference in potential has been effected between this position of the body and (the same body in) its former position.

Power: It will be noticed that work is independent of time. The time rate of doing work is called power. In the foot-pound-second system the unit is the horse power, (h. p.), which equals 33,000 foot-pounds in one minute or 550 foot-pounds in one second. It is based on experiments in which it was found that the work an average draft horse can perform continually without over-exertion is equivalent to lifting a weight of 150 pounds vertically while travelling at the rate of 2.5 miles per hour In the centimeter-gram-second system the unit is the **watt,** which is that power that will do one joule of work in one second. The large unit equals 1000 watts and is called kilowatt. This unit is employed in electrical work. 1 kilowatt= 1.34 h. p., or 1 h. p.,=746 watts =.746 kilowatts. Since energy is conserved, power can be supplied only by creating a difference in potential.

Transmission of Energy: In the mechanical world it is often desirable, for economical reasons, to create this potential difference at some central point, known as the power station, from which the power may be distributed by proper means to various other points and applied as required. For the transmission of energy there are four agencies, namely, gases, such as steam; liquids, such as water; electricity; and the Ether. In certain respects the characteristics exhibited by any one of these agencies in use is similar to each of the others. In the first case the difference in potential is maintained by making use of the potential, or chemical energy, of fuels to generate steam, which may be conducted through pipes to impart motion to engines and do work upon matter, or to give up its energy as heat. Similarly, water may be made to transmit energy by causing it to flow through pipes from high levels to lower ones. Somewhat analogous to the flow of the water, is the passage of the electric current along a wire. In each case means must be taken to maintain the flow by keeping up a difference in potential. In the case of water, a pump could be inserted in a circuit for returning the water to the higher level as rapidly as it flows

downward. In practice a pump would be impracticable, but the sun accomplishes the same thing by vaporizing water, so that it rises into the atmosphere to fall again as rain, and thus complete the circuit. In electric circuits this difference in potential is maintained by means of the electric battery, the static machine, or the dynamo, the last of which will be briefly described later. The close similarity between these two cases will be readily observed by a study of the following table of analogues, in which the water is assumed to be flowing through a horizontal pipe at the point of examination:

Table 44. Hydraulic—Electric Analogues.

Functions of the Currents		Hydraulic Units	Electromagnetic Units
Hydraulic	Electric		
Pressure	E. M. F. or Voltage	Pressure per sq. in. or Head in feet	Volt.
Quantity		Pound	Coulomb.
Rate of flow	Amperage	Pounds per second	Coulombs per sec. or Amperes.
Friction	Resistance to conduction	Loss in Head, No unit	Ohm.
Work	Electrical Energy	Foot-pounds	Joule.
Rate of Work	Wattage	Horse-power or watt	Watt or Volt—Ampere.

One important point of difference between the transmission of water and of electric current is evident; namely, that whereas water passes through a hollow tube, electrifications pass along solid bodies, usually wires. It is also common knowledge that electrifications will pass along some substances very easily and only with difficulty, or not at all, along others. No substance is so good a conductor as not to offer some resistance to the transfer. Substances that offer little resistance are called conductors; those in which the resistance is great, non-conductors or insulators. In the following table, the substances named are arranged in the order of their conductivities:

Table 45. Relative Conductivity of Various Substances.

Conductors	Salt water	Silk	Sealing-wax
Metals	Linen	India rubber	Rubber
Graphite	Cotton	Porcelain	Vulcanite
Acids	Dry wood	Air	**Insulators**
	Paper	Glass	

Electromotive Force (E. M. F.): While a definition of the various electrical units at this time would be out of place, occasion should be made to explain electrical pressures. Just as hydraulic pressure might be called water-moving force, so pressure produced electrically is called electromotive force (e. m. f.). As indicated above, the unit of measurement for electromotive force is the volt, which is also the unit for measuring difference in potential. In practice electromotive force and difference in potential are different things. Electromotive force refers to the total electrical pressure existing in a circuit, whereas difference in potential is merely the difference in electrical pressure between two points on the circuit.

SECTION II.

THE DEVELOPMENT OF ELECTROMOTIVE FORCES—OR "GENERATION OF CURRENT."[1]

Methods for Setting up Electric Currents: As already indicated the difference in potential between two points, which is necessary to produce an electric current, may be created by different methods, of which the most common and useful are the following: 1. By friction, as in the electrophorus, or electrostatic machine. 2. By chemical action, such as that which takes place in the electric battery, or voltaic cell. 3. By electromagnetic induction, as in the dynamo. In all these cases, energy must be expended to produce the difference in potential, and the points of different potential must be connected by a conductor. Electrostatic machines, while they produce a high electromotive force, generate only a small quantity of electricity in a given time. Current produced in this way has, therefore, a very limited use. In the voltaic cell these conditions of current are reversed, the amperage being high and the voltage low. The dynamo can be made to give current high in both voltage and amperage. It is, therefore, the most useful of all electrical machines, and is the source from which the current required by the electric steel furnace is obtained. This being the case, a discussion of the principles involved in the working of this machine should be both interesting and instructive. To an observer not familiar with the subjects of magnetism and electricity, the dynamo appears as a machine for changing motion into electrical energy, and, in a way, this idea is correct. But the generation of the current is not due to motion alone. Other phenomena, known as magnetism and induction, are involved, and to understand the generation of the current these must be studied first.

Magnetism: The attractive force of magnets upon iron is well known. Upon investigation, it is found that every magnet possesses two poles, designated as North and South, N. and S., or + and —, from which lines of force issue, and that these lines of force protrude into the space surrounding the magnet and extend from pole to pole. In studying the action of one magnet upon another, the following laws are observed: 1. Like magnetic

[1]For a fuller study of the generation, transmission and utilization of the electric current see the standard text books on Physics, also Practical Electricity by Terrel Croft and Applied Electricity for Practical Men by Arthur J. Rowland. Published by McGraw-Hill Book Company, Inc., New York.

poles repel one another; while unlike poles attract one another. 2. Lines of force having the same direction, i. e., issuing from like poles, repel each other; those of opposite direction, attract. All these facts are illustrated in the accompanying figures, which are diagrams made from photographs of actual conditions.

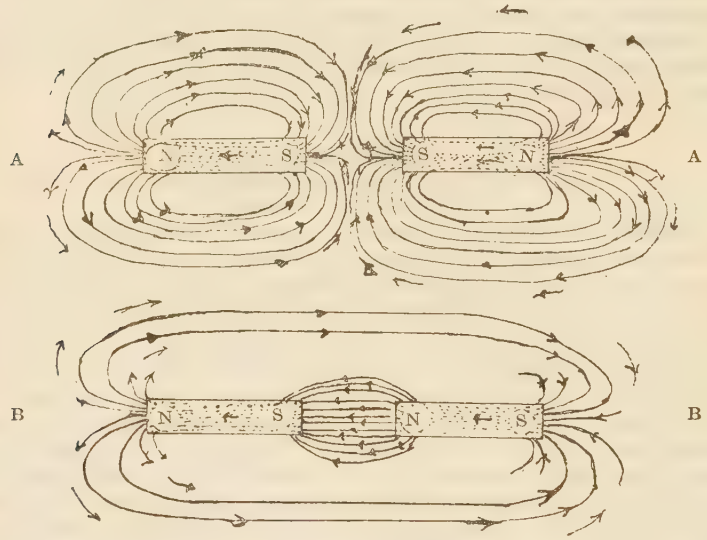


FIG. 92. Diagrams of Sections through the space surrounding magnets showing lines of force between like (A) and unlike (B) poles. Anyone may study these lines of force for himself by securing two bar magnets, some iron filings, and a piece of paper. The paper is laid upon the magnets and the filings are sprinkled upon it. The filings are thus magnetized and arrange themselves in lines or curves corresponding to the lines of force.

Magnets and Magnetic Substances: Magnets may be natural or artificial. Most magnets are artificial and may consist of straight bars or rods as shown in the figure, or be curved, as is the case with horse shoe magnets. These magnets may be either permanent or temporary. Permanent magnets are made of hard steel and retain their magnetism indefinitely, whereas temporary magnets are made of soft steel and are magnets only so long as they are under the influence of a magnetizing force. The space surrounding the magnet through which lines of force pass is called the magnetic field, and the number of lines is referred to as the magnetic flux. Substances that are attracted by a magnet or are magnetized when placed in a magnetic field are called magnetic substances. While it can be shown that most substances are affected by magnetism, iron, its alloys, and one oxide, Fe_3O_4, are the only substances available for use. These lines of force cannot be insulated, for they pass through all

substances, but by the use of a permeable substance, like very soft steel or iron, they may be deflected from their course and concentrated in the mass of iron as shown in A of Fig. 93.

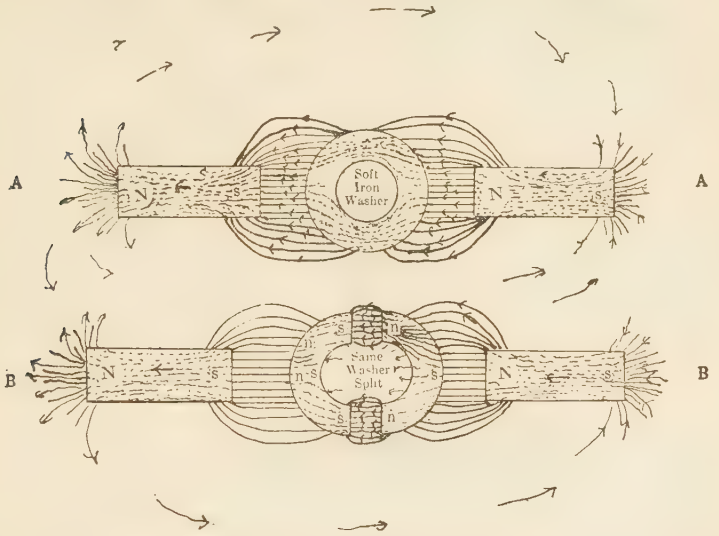


Fig. 93. Magnetic Permeability and Induction.
A. The soft iron washer encloses a space through which there are no lines of force.
B. Cut in two, the washer becomes a magnet by induction.

Magnetic Fields and Electric Currents: These magnetic lines of force are closely associated with the electric current, for it is easily shown that every current bearing conductor is surrounded by a magnetic field, the lines of force in which form circles concentric with the conductor. These lines of force have a definite direction as in the case of ordinary magnets, and this direction bears a fixed relation to the direction of the current, as shown in A of Fig. 94. This fact is made use of in producing the electromagnet, by coiling the conductor, properly insulated, about a core of soft iron, as shown in C of Fig. 94. Such a coil is known as a helix or solenoid, and has poles similar to magnets. The various relations between flow of current, lines of force, and poles of the helix are shown in the figure. The wide application of these facts cannot be discussed here, except in so far as they have to do with the development of an electromotive force, or, as this is more commonly referred to, the generation of the electric current. In connection with the generation of currents, this question might arise: If a current produces a magnetic field about a conductor, will the production of a magnetic field about a conductor result in a current? This question is now to be answered by a brief study of electromagnetic induction.

Electromagnetic Induction: The easiest way of bringing about such a condition as noted in the preceding paragraph is described in the following experiment: If a coil of many turns of fine copper wire is connected to a delicate galvanometer and one end of a bar magnet is thrust into it, the galvanometer needle will be deflected, showing that a current is set up in

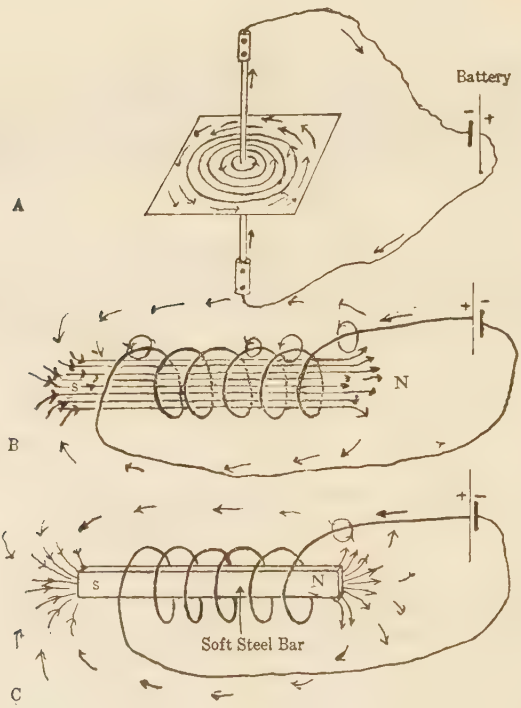


Fig. 94. Magnetic Fields About Current Bearing Conductors.
A. Lines of force about a wire carrying a direct current.
B. Lines of force in the current bearing helix.
C. The Electro-magnet. The lines of force pass into the soft steel bar, which becomes a magnet by induction.

the coil. As long as the magnet remains stationary, no current will pass. Upon suddenly withdrawing the magnet, however, a current will again pass, but the direction of this second current is opposite to that of the first. If these operations be repeated with the other pole of the magnet, similar currents will be induced, but in directions opposite to those obtained when the first pole is used. Instead of moving the magnet, the coil can be moved with a like result, and in place of the magnet a solenoid can be substituted. In the last case it may not be necessary to move either the solenoid or the

coil, as current can be set up in the coil by breaking the circuit or otherwise interrupting the current in the solenoid. From these facts it would seem that the sole cause of the current is the change in magnetic flux. Further study of these phenomena reveals the fact that the current induced is affected by the speed with which the magnet may be inserted and withdrawn, and the number of wires in the coil. In the case of the solenoid a third factor is introduced, as the current carried by the solenoid itself affects the induced current. Furthermore, no current is set up in the coil unless the motion is such that its wires **cut** the lines of force produced by the exciting elements: no current is generated if the conductor moves **along** the lines of force. All these facts are summed up in the following laws:

Laws of Electromagnetic Induction: 1. Any change in the number of lines of force passing through a closed conducting circuit induces a current in that circuit. (2) The direction of the induced current is always such that its magnetic field opposes the motion which produces it (Lenz's law). (3) The electromotive force of the induced current is directly proportional to the rate at which the number of lines of force are increased or decreased, or, the rate at which the lines of force are cut.

The Dynamo: Coming now to the practical application of these principles, it is found that, of the many electrical appliances depending upon them, the dynamo and the transformer are of chief interest in a study of the electric furnace. The dynamo is designed to convert mechanical energy into electrical energy. The steam engine, for example, does work on a dynamo, and the dynamo produces an electric current. This current contains all the energy that was received from the engine except a small percentage which was lost in heat and friction. There are three essential parts of a dynamo: 1st., the field magnets; 2d., the armature; 3d., the collecting brushes. The magnets are used to create a strong magnetic field between the two poles, that is, a field in which there are many lines of force.

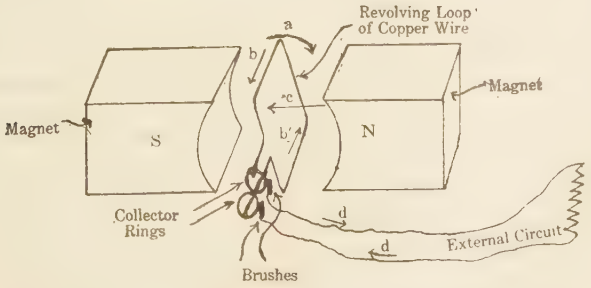


Fig. 95. Diagram Illustrating Essential Parts and Principle of the Dynamo.
a. Direction in which loop revolves. b and b'. Direction of current through loop.
c. Direction of lines of force. d and d'. Direction of current in external part of the circuit.

Hence, in all large dynamos electromagnets are used. The armature consists of coils of wire wrapped around a soft iron core; it is mounted so as to rotate in the magnetic field and cut lines of force. The current is thus generated in the manner described under induction. The essential parts of a dynamo are shown in the diagram of Fig. 95, which illustrates the arrangement for a drum wound armature. The north-seeking pole of the field magnet is marked N; the south-seeking pole, S. The armature is here a single loop of wire. The ends of the loop are connected to rings which rest on collecting brushes. When the loop is rotated, it cuts the lines of force, causing a current to flow out to the brushes and through the external part of the circuit. The direction of this flow bears a fixed relation to the lines of force, as explained under induction and as shown in the figure. In practice, the following rule is employed to determine the direction of the current in the armature: Extend the thumb, first finger, and middle finger of the right hand in such a manner that each will be at right angles to the other two. Place the hand in such a position that the first finger will point in the direction of the lines of force (N. to S.) and the thumb in the direction in which the conductor moves. The middle finger will then point in the direction in which the current flows.

SECTION III.

KINDS OF CURRENT.

Alternating Current: The current produced in the dynamo armature is not a constant one and travelling in one direction, such as is obtained by means of batteries, but is an alternating one, as a further study of Fig. 95 will show. Let the coil be rotated as indicated by the curved arrow above it. While the side at b is moving downward in front of the pole N., the side at b′ will be moving upward in front of the pole S. An application of the law for direction shows that the currents thus induced by the two branches of the coil cutting lines of force will flow in opposite directions in relation to each other, but in the same direction from end to end around the coil. This current continues as long as **b** and **b′** are moving in the same direction across the lines of force—that is, during one-half of one complete rotation. Then, as the rotation continues, the sides of the coil cut the lines in an opposite direction, and the current is completely reversed. Each time the coil is turned half way around, the direction of the current is changed. Each end of the coil is attached to a ring. The rings are attached to the axis of the coil and rotate with it. Brushes slide upon the rings and conduct the current out upon the line of the external circuit. The line current is thus changed in direction twice during each complete rotation of the coil or armature. Each change in direction is called an alternation. Two alternations constitute a cycle—that is, a circle or series of changes which will be repeated in the next cycle. The time required for one cycle is the period. The number of cycles in

one second is the frequency. The frequency is one-half the number of alternations in one second. In modern forms of alternators the frequency is seldom more than 60 nor less than 25 cycles per second. To produce 60 cycles in a second with a machine like that shown in Fig. 95, the armature would have to make 3600 rotations in one minute. To avoid such high speed, a number of pole pieces are arranged in a circle around the armature, making what is called a multipolar machine. These poles are wound so that north and south-seeking poles alternate in position. A cycle is then produced in the circuit by the passage of any two adjacent poles. If there are ten poles, there are five cycles during one rotation of the armature. A current of 25 cycles per second would mean 50 alternations per second or 3000 per minute; on a two-pole machine it would require 1500 r. p. m.; on a 10-pole, 300 r. p. m. The latter is about as low a speed as a machine can be operated upon economically. These are some of the reasons why it is not practical to operate alternators on cycles over 60 nor under 25.

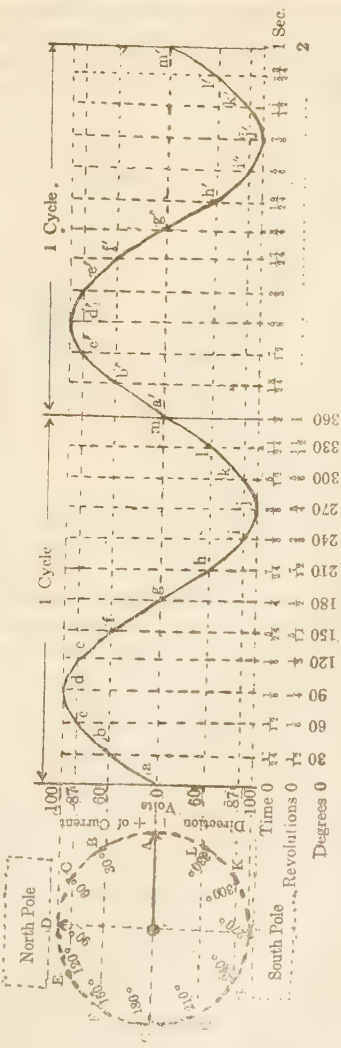


FIG. 96. Diagram illustrating the sine curve used to represent the fluctuating voltage and amperage of an alternating electric current. This particular curve is for voltage. The curve for the amperage would be similar, but unless the resistance is one, the numerical values would be different.

Graphic Representation of Alternating Current: The surges of the current are approximately harmonic, hence the electromotive force may be represented by the sine curve, as shown in Fig. 96. This figure shows one complete wave or cycle, as taking place in ½ second of time, and going from zero through a positive maximum and back to zero, where it continues to a negative maximum to return again to zero, thus completing a cycle. In actual currents the time of a cycle is much less than ½ sec., i. e. 1/25 or 1/60 sec., because the speed of the armature is greater and a cycle is completed every time it passes a

pair of poles. The different stages of vibration represented in the graph are spoken of as phases. Thus b and b′ are in the same phase, but b and h′ are in opposite phases, etc.

Direct Currents: While all dynamos produce alternating current in the armature, this current may be changed to a direct one by means of a commutator properly connected to the armature. How this is done can be understood by a study of the accompanying figure.

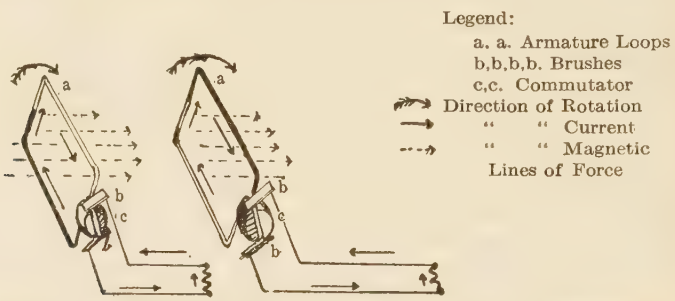


Fig. 97. Diagram Illustrating how Current is Rectified by means of a Commutator. For reasons to be given later, direct currents are not used in furnaces for refining iron and steel.

Polyphase Currents: In order to increase the efficiency and output of alternators, recourse is had to polyphase current. These currents are the result of attempts to put to economic use the interpolar space, or surface of armature core, which is only partly filled in by conductors in single phase machines. In any given machine of this kind, which involves certain given mechanical and magnetic losses, approximately only half of this space is utilized. This waste of space and consequent inefficiency can be removed by utilizing the space devoted to the core of the coil for the winding of other coils, and thus form a second armature of an equal number of coils overlapping the former and utilizing the same magnetic field. In this second armature the phase of the current would be a quarter period, 90 degrees, ahead or behind that of the first, and so would require four wires to carry the currents to and from the generator. The output of the machine, however, has been doubled. Further attempts to increase output have resulted in electrical engineers going even further and constructing triple armatures, in which the phase of the currents generated differ by equal intervals of ⅙ of a period, or 60 degrees. But this scheme then leads to considerable elaboration, if the circuits be totally independent with six conductors, and very little advantage could be shown to exist over the two-phase with four lines. However, in cases where it is possible to arrange that the demand in the different circuits be approximately equal and evenly distributed, the three-phase system can be worked out to great advantage by using only three conductors. By referring to the accompanying diagrams (Figs. 98 and 99) it will be seen that, at any moment whatever, the sum of

the electromotive forces in the three circuits is zero. In other words, the electromotive force on one line is always equal to that on the other two, and opposite in kind. Thus, at any instant one of the three wires is to be looked upon as the return wire for the other two.

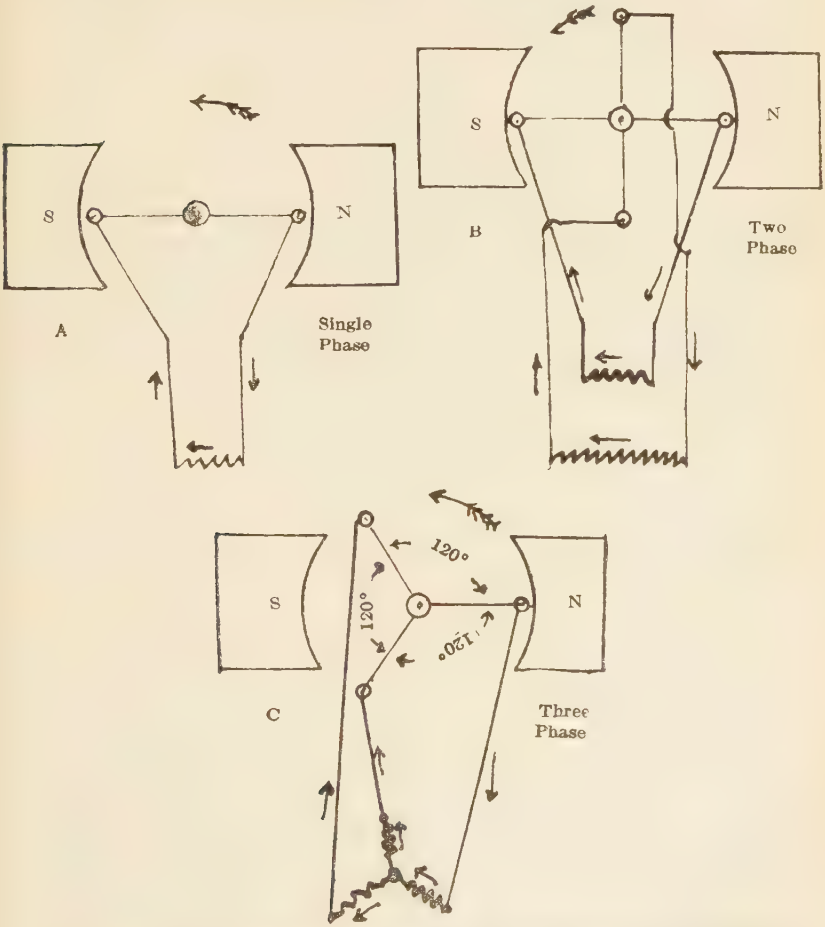
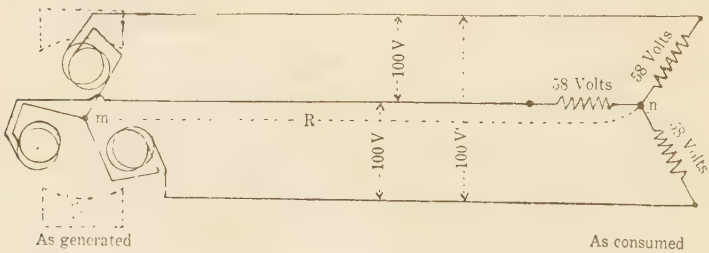


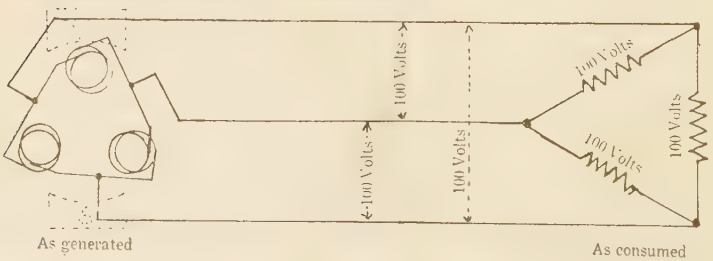
FIG. 98. Diagrams Illustrating the Methods of Generating the Three Kinds of Alternating Current.

The Two Schemes of Wiring for Three-Phase Current: The coils of the three-phase current alternator, as well as those of the apparatus that is to consume the power, may be connected in two different ways with each other as shown in the following diagrams. In these diagrams the three-phase generator is considered as a compound machine made up

of three separate machines. In such a machine, the separate units may be wired independently as shown in Fig. 99A. Instead of three return wires, one common return wire may be employed, as shown by the dotted line R in the figure. But it is found that, with balanced loads on each system, R is a neutral line, that is, no current flows through it; consequently, it is omitted as in the figure. The points m and n are therefore called neutral points. The form of this diagram suggests the name for the scheme, which is known as the star, or Y, connection. In the other schemes the coils of the dynamo are connected in a series, and the power is led off through mains connected to points in the connecting lines. Fig. 99B shows diagrams intended to illustrate the scheme for this connection. On account of the similarity to the Greek letter Δ, this scheme is known as the delta connection. It is also called the V and mesh connections. It will be observed that the windings of the delta connection form a closed circuit, and the generator therefore appears to be short circuited. However, such is not the case, because, owing to the fact that the currents generated by the three windings differ in phase by 120°, as shown in Fig. 98C, the resultant of the three voltages is at every instant zero, hence no current can flow by way of the short circuit. With this plan of connections the load may be balanced or unbalanced, as each coil or set of windings supplies its own load.



A. Diagram of Star (or Y) Connections.



B. Diagram of Delta (Mesh or V) Connections.

FIG. 99. Diagrams Illustrating the Two Methods of Winding and Wiring for Three-Phase Currents.

These connections are of importance in understanding how the power of three-phase currents is transmitted. They also affect the voltage employed,

the relations being as shown in the preceding diagrams. The Duquesne furnace, for example, operates on 104 volts with star connections and 180 volts with the delta. This care in explaining three-phase current has been taken, because it is the most common kind of current and is used in the Heroult furnace, the details of which will be explained later.

SECTION IV.

TRANSMISSION OF THE CURRENT.

Ohm's Law: With this brief explanation of the generation of the current, it will be well to turn next to the problem connected with its transmission. Here, also, it is necessary to begin with the simplest essentials. The most fundamental idea in this connection can be briefly stated in the form of a law, known as **Ohm's law.** This law states that the strength of current passing along a conductor varies directly as the electromotive force, or drop in potential, and inversely as the resistance. This law is generally put in the form of a formula, thus:

$$I=\frac{E}{R} \qquad \text{or} \qquad \text{Current}=\frac{\text{Electromotive Force}}{\text{Resistance}}$$

In place of these letters the units which are used in measuring the quantities they represent may be substituted, thus:

$$A=\frac{V}{O} \qquad \text{or} \qquad \text{Amperes}=\frac{\text{Volts}}{\text{Ohm's}}$$

By the use of this formula any one of the three quantities may be found, provided the other two are given. It may be applied to an entire circuit or to a part of a circuit.

Resistance of Conductors: Referring now to resistance of conductors, it will be recalled that, as previously stated, all conductors offer resistance to the passage of the current. This resistance can be calculated by applying the following law, which has been developed by many experiments. It is stated as follows:—The resistance to the flow of an electric current along a given conductor at a given temperature varies directly as the length and inversely as the area of its section, and is different for different substances. As a formula, the law is expressed thus: $R=\frac{Kl}{d^2}$ where R= resistance, l=length, d^2=square of the diameter, which is directly proportioned to the area, or the area itself, and K=specific resistance of the substance. In the foot-pound-second system, l=length in feet, and d=diameter in **mils,** or thousandths of an inch. **A circular mil** is the area of a circle one **mil** in diameter. So if the diameter of a wire is expressed

in mils, d^2=the area in circular mils. The **circular mil** is not to be confused with the **square mil** which is the area of a square having sides 1/1000 inch long. The area of a circle in square mils, the diameter of which is expressed in mils $=\frac{\pi d^2}{4}$. In this connection the following formulas may be found of assistance:

1. sq. mils=cir. mils$\times$0.7854 2. cir. mils$=\frac{\text{sq. in.}}{.0000007854}$

In wire, a length of one foot and a diameter of one mil constitutes a **mil-foot.** The specific resistance of any substance is the resistance of one mil-foot. In the following table are the specific resistances of a few substances, determined for this system, at 60° F. In the metric system, l=meters, d^2=sq. millemeters, and, of course, K has a numerical value different from that by the foot-pound-second system, as shown in the table.

Table 46. Specific Resistance of Various Substances.

	60° F. Foot-Pound-Second (F. P. S.) System	0° C. Centimeter-Gram-Second (C. G. S.) System
Silver	9.53	.017
Copper	10.35	.018
Aluminum	.....	.03 to .05
Gold	13.34	.....
Zinc	36.46	.06
Iron	.....	.10 to .12
Platinum	58.00	.12 to .16
Steel	63.00	.10 to .25
Molten Steel	.....	1.66 to 2.2 at 1700° C.
Nickel	.....	.15
Lead	127.2	.22
German Silver	135.0	.15 to .36
Mercury	616.16	.94073

The Ohm, the unit of resistance, may now be defined. It has been established by law to be the resistance offered by a mercury column 1.063 m. long of 1. sq. mm. cross section, and at the temperature of 0° C. Originally, the length of the mercury column was one meter.

Effect of Temperature on Conductors: In connection with the effect of temperature upon conductors, it should be noted that there are two classes of substances, known as conductors of the first class and conductors of the second class. In conductors of the first class, which includes all the metals, the resistance increases with a rise in temperature, hence their conductivities decrease. This is shown in the case of steel, which at 15° C.

has a specific resistance of only .10 to .12, whereas at 1700° the specific resistance of the molten metal is about 1.66. In the case of carbon and conductors of the second class, these relations are reversed, so that they become better and better conductors as their temperatures rise. As all the refractory materials that go into the construction of furnaces belong to this class, this matter must be carefully considered in building electric furnaces.

Resistance in Series and Parallel: In the preceding paragraph, only single substances were considered in the circuit. In the actual distribution and use of power, it is generally necessary to divide circuits, in which divisions different materials or machines will also make up a part of the circuit. This division and connections can be made in two ways, namely, series and parallel, as shown in the following diagram illustrating two methods of light wiring.

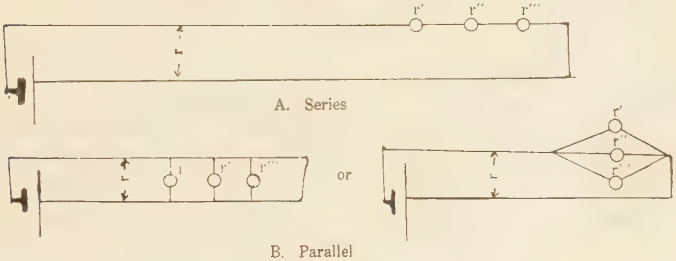


Fig. 100. Diagram Illustrating Different Methods of Wiring.

In Fig. 100A, the resistance of the line is r and of each of the lamps it is r', then the whole resistance, R, is the sum of these four, or

$$R=r+r'+r''+r''' \text{ or } R=r+3r'.$$

Resistance of conductors connected in parallel is not found so simply. It is deducted from the law of conductivities, which states that the conductivity of a combination of conductors is equal to the sum of the conductivities of the conductors singly. Now, it is self evident that the conductivity is represented by $\frac{1.}{R}$ The resistance in the parallel connections above would then be found by solving the following:

$$\frac{1}{R}=\frac{1}{r}+\frac{1}{r'}+\frac{1}{r''}+\frac{1}{r'''}$$

This matter is of importance in dealing with electric furnaces, as shown

in the following schematic diagram of the wiring of Heroult and Girod furnaces, which marks the chief difference between these two furnaces.

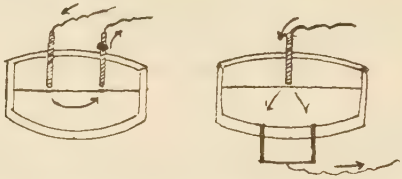


Fig. 101. Wiring Diagrams for Heroult and Girod Electric Steel Furnaces

These diagrams show the Heroult furnace, on the left, to be connected in series and the Girod in parallel.

Currents Through Divided Circuits: If the different parts of parallel connected conductors have equal resistance, then equal currents will flow through these parts, as is evident from Ohm's law, thus,

$$I=\frac{E}{R} \qquad I'=\frac{E}{R'}$$

As the current s always delivered at a constant voltage, E is the same in both cases; hence, if R=R′, I=I′. If the resistances are not the same, then I would not equal I′. The current flowing in each conductor, however, can be found from the following law: Currents which flow parallel to each other vary inversely as the resistance of the parallel connected conductors.

Self-induction, Impedance, Power Factor: In dealing with alternating currents, Ohm's law does not hold, for the alternations cause **self-inductance** in the conductor, that is, they generate currents opposite in direction, or kind, to that of the main current; and this inductance also offers resistance to the current in addition to that offered by the conductor. The sum of these two forces opposing the passage of the current is called **impedance.** If impedance be substituted for resistance, then Ohm's law holds for alternating currents, also. Again, any self-induction in the circuit causes a difference in the phase between the electromotive force (voltage) and the current (amperage), so that the latter either forges ahead of or lags behind the former, and the two do not reach their maxima and minima together. Consequently, their product at these points, which represents the energy available for consumption, is less than the total energy supplied. The ratio, expressed in per cent., between the useful voltage, or that which is required to overcome the resistance of the conductors and to produce the heat or do any other work desired, and the actual voltage required is called the **power factor.**

Heat Developed in Conductors: Since all conductors offer resistance to the flow of the current, work is done in overcoming this resistance. In doing this work part of the electrical energy is converted into heat energy, just as work is done and heat developed in overcoming friction. This heat

can be calculated by means of Joule's law, who found from many experiments that the heat developed by a current flowing through a conductor is directly proportional to the time, to the resistance, and to the square of the current. Mathematically stated, this law is $H=K\ I^2\ RT$, where H=heat, I=current, R=resistance, T=time, and K=a constant, which Joule found to be .24. Since from Ohm's law, $I=\frac{E}{R}$ or $E=IR$, H=.24 IET calories, when I is measured in amperes, E in volts, and T in seconds. The heat thus developed is of much importance in the transmission of current, for if the current be sufficiently large this heat may raise the temperature enough to burn off the insulation, or even to melt the wire. This heating can be overcome in two ways. In the first method, the diameter of the conductors could be increased, which would decrease the resistance and increase the carrying capacity. That this method has its limits is evident, due to the immense weight of wire required in some cases where large current (amperage) is required, as is the case with electric furnaces. The second method is applicable to alternating current only and illustrates both the adaptability of the electric current in general and one advantage of alternating current in particular. From Joule's law it is evident that a current of large voltage may be carried on a given wire provided the density, i. e., amperage per circular mil or square millimeter be kept low. Since power=amperes$\times$ volts, or for alternating current Power=amperes$\times$volts$\times$power factor, this can be done without reduction in power. But since the furnace requires a current of low voltage and high amperage, such a current could not be used unless means be taken to change this high-voltage-low-amperage current into one of low voltage and high amperage. How this is done can be learned from the following description of the transformer.

The Stationary Transformer: In this instrument the desired transformation is effected by electro-magnetic induction already discussed. Of course, then, only those currents which are started and stopped or increased and decreased in rapid succession, or those in which the direction of the current is changed many times in a second, can be transformed. Such current is furnished by the alternator. In structure the transformer consists of two coils of wire side by side with a core composed of many sheets of soft iron, or a special silicon steel, packed together. The coils must not have any metallic connection with any part of the instrument. The first coil, that through which the main current flows, is called the primary. The second coil, or that in which the current is induced, is called the secondary.

Kinds of Stationary Transformers: Transformers are of two kinds—step-up and step-down. The step-up transformer increases the voltage and decreases the amperage. The step-down produces the opposite effect. The change depends on the relative number of turns of wire in the primary and secondary coils. If, for example, there are 100 turns in the primary and 1000 turns in the secondary, the voltage will be increased 10 times

and the amperage decreased 10 times. This is then a step-up transformer. A step-down transformer would reverse these conditions throughout. If there are the same number of turns in both coils, the current will not be changed except as it may be affected by the transformer efficiency, which should be about 98 per cent.

In regard to the power of the transformed current it will be seen that, since, whenever the transformer increases or decreases the voltage, it decreases or increases the amperage, the number of watts will be a constant quantity. Suppose there is a current of 100 volts and 10 amperes flowing through the primary. The power is then 1000 watts. If the transformer raises the pressure to 500 volts, the strength of the current will fall to 2 amperes, but the power of the current is still 1000 watts. A good transformer gives out nearly all the energy that is put into it. A small percentage, varying from 2 per cent. to 5 per cent. of the voltage, is converted into heat. Usually this heat is prevented from collecting by immersing the coils in cylindrical tanks of oil so constructed as to form a circulating system through pipes extending externally from the top to the bottom of the cylinder. These pipes act like a hot water radiator and serve to keep the whole bath and its contents cool. The oil also serves as an insulator. For steel furnaces three-phase 25 cycle current is stepped down from 6600 volts to 104 on the star connection or 180 on the delta, the latter of which is seldom used on molten charges.

SECTION V.

THE UTILIZATION OF THE CURRENT IN ELECTRIC FURNACES.[1]

Effects Produced by Electric Current: The heating and magnetic effects of electric currents have already been touched upon in connection with generators, conductors and transformers. In order to understand how the electric current is utilized in electric furnaces it is necessary to study these and other effects from a slightly different standpoint; namely, their effect upon the metallic charge in the furnace itself. In this connection it may be truly said that there is but one other effect produced by the electric current, and this effect is that of bringing about chemical action. To the question as to what chemical action is caused by the current in the bath of steel, the correct answer is: There is none. As this answer is not in accord with chemical effects produced by currents in many other metallurgical operations, an explanation may be necessary.

Chemical Action Produced by the Electric Current: As pointed out in Chapter I, electrolysis is brought about when electric currents are passed through liquids under certain conditions, some well known examples being the dissociation of water and the electrolytic separation of aluminum.

[1]For a full discussion of electric furnaces See The Electric Furnace, by Alfred Stansfield, Published by McGraw-Hill Book Co., Inc., New York; Electric Furnaces in Iron and Steel Industry, by C. H. Vom Baur, published by John Wiley & Sons, New York; and Electric Furnaces for Making Iron and Steel, by Dorsey A. Lyon and Robert M. Keeney, Bureau of Mines Bulletin 67.

In these instances, however, it will be observed that these chemical changes occur only when direct current flows through the electrolytes. If alternating current is used, then the direction of the current is constantly changing, and no action, such as noted above, can take place. Furthermore, such action would be harmful in carrying out the electro-thermal process for steel. While it might be possible with direct current to purify the metal by removing the impurities as sulphides, silicides, and phosphides, there would be no way of controlling the process so as to prevent the reduction of lime, alumina and other oxides, the elements from which would then find their way into the metallic bath. This reduction would result in a more impure product than the raw material. Designers of electric furnaces for the iron industry will, then, use alternating current exclusively and strive in every way to prevent any electrolytic action that might result in electrolysis.

Electrical Units of Measurements: The subject of electrolysis offers an opportunity to define another of the primary units used in electrical measurements. The ohm has already been defined in studying resistance. It now remains to explain how the value of the ampere is fixed. If a current be made, by means of suitable electrodes, to pass through a solution of silver nitrate, metallic silver will be deposited upon the cathode, or positive pole, and the amount of silver thus deposited in a given time will be proportional to the strength of the current. This fact has been made the basis for fixing the value of the ampere. The legal definition reads as follows:—The **ampere** is that current which when passed through a 15-per cent. neutral solution of silver nitrate will deposit .001118 grams of silver in one second. **The volt** is then legally defined as the e. m. f. which will cause a current of one ampere to flow through a resistance of one ohm. In fixing the value of these units, it was arranged so that the power possessed by a current of one ampere under a pressure of one volt is just equal to one watt. Hence the power of the current in watts equals the product of the amperage and voltage, or $W=V\times A$. The **watt-hour** is the energy expended in one hour when the current is one ampere and the voltage, or pressure, one volt. Hence, 60 watts used for one min. or one watt used for 60 min. will give one watt hour. A **kilo-watt-hour**=1000 watt hours.

The Magnetic Influence of the Current can be of but slight importance to the metallurgist. To the designer of induction furnaces they are of double importance. On account of a certain motor effect which they produce in the molten metal, these forces cause what is known as the pinch effect which will often break the circuit. In arc furnaces this motor effect is present in the immediate vicinity of the electrodes causing a slight motion of the bath.

Heating the Bath: It is to be understood, then, that the only use to which the current is applied in the manufacture of steel is for the generation of heat. It may be well, therefore, to consider briefly the heating possibilities of the current in connection with its practical application to this

purpose. A little thought shows that these possibilities are only three in number, and may be called heating by direct resistance, heating by indirect resistance, and heating by means of radiation from an arc or arcs. A brief discussion of the three methods, which is also made to serve as a means of describing the principles of the many makes of furnaces, follows:—

Heating by Direct Resistance: In the method of heating by direct resistance, the necessary heat to keep the bath molten is produced by making use of the resistance of the iron itself. In some respects this method would appear to offer some advantages. 1. Since heating is effected by the passage of the current through the liquid metal, the heat would be uniformly distributed throughout the mass. 2. Since the heat generated is proportional to the square of the current, the amount of heat could be regulated by changing the resistance of the furnace. 3. Very low voltage currents could be used. But the disadvantages outweigh the advantages, as will be realized better if they are set along side the advantages, thus: 1. As the specific resistance of iron is low, the high temperature required could be obtained only by the use of very high amperage, which would require exceedingly heavy connections. 2. This draw-back could be overcome by increasing the length of the bath and decreasing the cross sectional area; but such an arrangement has been found impracticable on account of the large area the bath then covers, which results in great heat losses and precludes the easy change of slags and handling of the metal. Hence, all early attempts to employ direct resistance for heating proved failures. The problem was, however, eventually solved by the invention of the type of furnace known as the induction furnace. In these furnaces the bath is made to form the closed secondary circuit of a transformer. This secondary can then consist of but one coil, as shown in the following diagram illustrating the principle of the induction furnace as invented by Colby and Ferranti and later improved and adapted to the manufacture of steel by Kjellin.

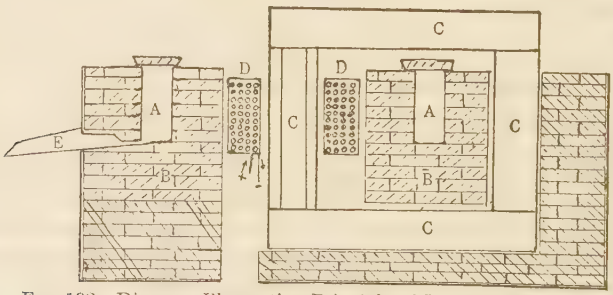


Fig. 102. Diagram Illustrating Principle of Induction Furnaces. Vertical Section of Kjellin Furnace.

The furnace includes a magnetic circuit, C, formed of the usual laminated sheet iron, as in a transformer core. Electric energy is supplied to a primary coil, D, while the secondary circuit is formed by the ring of

metal under treatment, contained in the annular cavity, A, forming the crucible. Now, when energy, in the form of alternating current is supplied to the primary coil, D, it creates a varying magnetic flux in the laminated iron core, which in turn induces a current in the closed secondary circuit consisting of metal in crucible A. The current density in the secondary bears a fixed ratio to the number of turns in the primary coil D, so that it is possible by a suitable variation in impressed voltage to subject the metal to an extremely heavy current density, the heat being thus produced in accordance with Joule's law simultaneously throughout the entire mass of the metallic bath. Because of the limited contact area between slag and metal, this type of furnace does not readily lend itself to refining processes, if the form shown in the figure be adhered to. However, this form was later changed so as to give a central hearth of considerable size. Those who have designed furnaces with the object of improving the Kjellin type are Frick, Hiorth, Harden, Greene, and others. On account of the low specific resistance of iron, it is difficult to reach high temperatures in these furnaces. They are, therefore, not well adapted for desulphurizing operations in which sulphur is removed as sulphide.

Indirect Resistance Heating offers a second possibility. Instead of depending upon the resistance of the bath alone to furnish the heat required, some other conductor having a high resistance might be built into the furnace in such a way that the heat generated in it would be absorbed by the material to be heated. This is the principle employed in many laboratory furnaces and in large furnaces for manufacturing carborundum. But in applying the method to the manufacture of steel several insurmountable difficulties are presented. 1. The resister can not be composed of carbon and in contact with the metal, on account of the absorption of this element by iron. 2. If a suitable resister of another material could be found, it could not be placed in the bath, because it would then be in parallel with the metal. The only way these difficulties can be overcome is by the use of crucibles to contain the molten metal. The impracticability of this method is at once evident, and furnaces of this type designed for manufacturing steel have met with no success.

Arc Heating: The use of the electric arc, which has been mentioned as the third possibility for producing heat, is the simplest and the most practical of all and has found the widest application in the steel industry. Some information as to the nature of electric arcs should, therefore, be interesting. In beginning, a distinction is to be made between electric sparks and electric arcs. While the air is practically a non-conductor, it is possible to create such a high difference in potential between two given points as to cause a current to jump the gap and establish equilibrium. Such conditions occur in electrical storms, and lightning is an example of electric sparks. In arcs the current also appears to pass through the air but it will be observed that a much smaller voltage is required to form an

arc than is needed to cause sparks. The most common example of the arc is the arc lamp. Here the arc is made between two carbon electrodes, but in order to strike an arc it is necessary to bring the electrodes into contact, after which a gap may be gradually produced and the arc still maintained. If the gap becomes too wide, however, the arc will break, hence means of regulating the distance between the electrodes must be provided. Evidently the air is not the conductor in arcs as in sparks. All these phenomena are explained by assuming that some of the electrode material is vaporized by the heat of the arc, and that these vapors serve as a conductor of the current. Some idea of the intensity of the heat of this arc, which gives the highest temperatures yet attained, is to be had from the fact that carbon vaporizes at about 3500° C.

Methods of Applying the Arc in Arc Furnaces: Furnaces of this type, then, depend almost wholly upon this high temperature of the electric arc for the heat required by iron and steel baths. The following diagrams will illustrate the three possible methods of applying the arc and heating the bath.

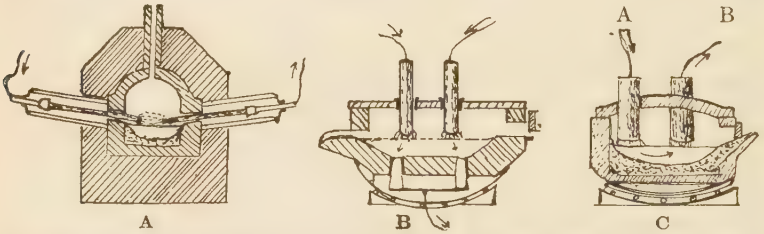


FIG. 103. Diagrams Illustrating the Three Ways of Employing the Electric Arc in Steel Furnaces.

In each of these three cases the bath is directly beneath the arc or arcs and receives its heat mainly by radiation. All three possibilities are practical and have been successfully applied. So these same figures also illustrate the principles of the three furnaces of the arc type.

The Stassano Furnace is represented in principle by Fig. 103A. The distinguishing feature of this furnace is that the current does not pass through the metal or slag, the heating being accomplished entirely by radiation. At first, Stassano built his furnaces so that they could be rocked or rotated in order to agitate the bath, but as this feature did not prove to be of any advantage, it has now been abandoned. His furnaces are now of the tilting type. In practice three-phase current is generally used, and the three electrodes enter the furnace at an angle through the walls. This plan has the effect of placing a limit to the size of the furnace, and so few of these furnaces with a capacity greater than two tons have been built. From an electrical standpoint, the furnace possesses the important advantage of uniform power consumption, thus avoiding harmful fluxuations in current.

Girod Furnaces: The furnace scheme shown in Fig. 103B has been developed by several inventors. It was first successfully introduced by Girod for the purpose of manufacturing ferro-alloys. As shown in the figure the electrodes are inserted in both the top and the bottom of the furnace, thereby connecting electrodes, slag and molten metal in series. Heat is thus produced in three ways, theoretically at least. By means of an arc at the top, the greater portion of the heat is generated. After forming the arc, the current, in its downward courses, must pass through the layer of slag which, through the heat of the arc above, becomes a conductor of the second class, after which the current is conducted by the molten metal to the electrodes at the bottom. In furnaces using a single phase current, these bottom electrodes are four or six in number and are equally spaced about the periphery of the hearth. In the three-phase furnaces there are four upper electrodes, two of which must be in parallel, and sixteen bottom electrodes. In all cases the bottom electrodes are made of steel and are water cooled. Other designers of this type of furnace are Keller, Grönwall, Nathusius, Stobie and Soderburg.

The Principle of the Heroult Furnace is diagrammatically represented in Fig. 103C. The practicability of this principle is shown by the fact that the Heroult electric steel furnace heads the list of such furnaces in use for the manufacture of steel. This popularity of the Heroult furnace is due to the fact that the application of this principle gives a furnace of the greatest efficiency combined with simplicity of construction and adaptability to many different uses. Details of the construction of this furnace will be given later. At present it is desired to explain only the method of heating. All the electrodes, as indicated by the figure, are suspended from supports over the roof, through which they project to within an inch of the surface of the slag. As the electrodes are so far separated from each other as to prevent arcs between them, several resistances are introduced in series. For example, let the current be considered as passing from A to B. Then as the current jumps the gap at the foot of A, it forms an arc and passes into the slag, which also has a high resistance. The metal, having a much lower resistance, then acts as a conductor for the current to the region directly beneath the foot of electrode B, where the current must again pass through the layer of slag and form a second arc as it jumps the gap between slag and electrodes. It is evident that practically all the heat is formed by the arcs above the slag, **which acts as a shield to the metal** and protects it both from the carbon vapors thrown off from the foot of the electrode and from the exceedingly high temperature at this point. Portions of this heat is next imparted to the metal through the slag, where it may be distributed to all parts of the bath by conduction and convection. The distribution of the heat is thought to be aided by a slight motor effect produced by the current upon the metallic bath. Furnaces of this type using single-phase and three-phase current are in use. The only change necessary to be made for three-phase current is the insertion

of a third electrode. In the development of these furnaces Heroult stands almost alone, though slight modifications have been introduced by Chaplet and Anderson.

Some General Conclusions: From what has been said, the following facts are evident: 1. That the only part the electric current plays in the manufacture of steel is in the production of heat. 2. That for producing this heat there are really but two methods available, which has resulted in two successful types of furnaces, namely, the induction type and the arc type. 3. That from a strictly metallurgical point of view no one of these types represents any marked advantage over the other, in their present high state of development. This statement has no relation to claims of the inventors to mechanical and electrical points of excellence in their respective apparatus. What advantage electric heating has over other methods of heating is now to be discussed.

SECTION VI.

GENERAL FEATURES PERTAINING TO THE METALLURGY OF STEEL MADE BY ELECTRO-THERMAL PROCESSES.

Advantages of Electric Heating: To the metallurgist the electric method of heating is an ideal one for the following reasons, which are characteristic of it: 1. It makes heat available very quickly and at will, and gives an unusually high temperature. 2. The heat may be regulated very nicely, which fact permits a charge to be brought to any temperature desired and to be maintained steadily at that temperature. 3. Being the cleanest of heating agents, it exerts no delcterious effect upon the material heated by the evolution of harmful gases. 4. It permits **oxidizing, reducing** or **neutral** operations to be carried on at will. How these characteristics of electric heating work to the advantage of the metallurgist and permit him to obtain a product of the highest quality from raw materials of any grade will be understood from a study of the topics to follow. In this connection the chemical possibilities are of first importance.

Refining Procedure: The first effect of the characteristics noted above is to bring the whole operation of refining metal under the control of the operator. The electric furnace is to the metallurgist what the casserole and crucible are to the chemist. The bath, then, represents a mixture of compounds and elements, any one of which may be removed at will by the use of the proper reagents. The condition may be illustrated by assuming a furnace is to be charged with the crudest of raw materials, cold pig iron, and then showing how each impurity is removed. A study of the practice of many plants shows that the following procedure would be carried out: After the furnace has received its metallic charge, an oxidizing flux of lime and iron ore will be added. A part of this flux may be charged ahead of the metal, exactly as in the case of the basic open hearth. After the charge

has been melted down, the furnace will be tilted slightly and the slag which has formed will be carefully raked off. This addition of flux and removal of slag will be repeated as often as may be necessary. A cleansing flux of lime alone will then be added and raked off. During this period the temperature should be kept low, because phosphorus is not readily oxidized at high temperatures in the presence of carbon. The bath will then be covered with a flux consisting of about 5 parts lime, 1 part sand or other form of silica, 1 part fluorspar, and ¼ part of carbon in some convenient form, such as coke, coke carbon, old electrode, etc. The furnace will then be tightly closed, and the temperature raised. In the case of induction furnaces, it will be found necessary after about two hours to introduce small portions of ferro-silicon, silico-aluminum, or silico-spiegel. These alloys act energetically as deoxidizers and form a fluid slag which rises to the surface. In the Heroult furnace carbon is the only deoxidizer used. After the steel shall have been thoroughly deoxidized, any carburizing material or alloys will be added to bring the steel to the desired composition. When all such material will have been melted, and sufficient time will have elapsed to permit them to mix with the bath, the molten steel will be poured as a finished ingot product. This process divides itself into three distinct periods, namely, an oxidizing period, a reducing period, and a finishing period, a combination of conditions impossible of attainment in any other steel making process. The action brought about during each of these periods, and the reasons for using the reagents employed may now be discussed.

The Oxidizing Period: It is evident that the action of the oxidizing flux must result in the removal of silicon, manganese and phosphorus in a manner similar to that of the basic process. The important distinction between open hearths and electric furnaces should be noted here. It is this: All the oxygen introduced into the electric furnace must be in the solid form as observed above, and the amount can be easily controlled, whereas the air admitted to open hearths furnishes an unlimited amount of oxygen that cannot be controlled. Therefore, since these three elements are easily oxidized at low temperatures before the carbon, the reaction may be stopped and the bath held at almost any carbon content desired. With respect to phosphorus, it has been suggested that this element may be removed as phosphide by means of some metal, as calcium. While this scheme is theoretically possible, it is still impracticable, for it is a difficult thing to find a metal that would not alloy with iron in preference to combining with phosphorus, or whose phosphides would not so alloy. Quite frequently, traces of phosphorus are found in the reducing slags, but this method of eliminating phosphorus, though often attempted, has not been made successful beyond the removal of very small amounts and at great expense. Hence, the only sure way of removing this element is to oxidize it to phosphoric acid, neutralize with lime, and rake off the resulting slag. In refining purer materials than pig iron, where the removal of silicon

and manganese would not be required, the oxidizing slag is called the dephosphorizing slag. Considerable sulphur is removed during this period in the electric furnace, especially where an ore high in manganese is used, whereas in the basic furnace, its removal is a very uncertain quantity.

The Reducing Period: This is the period in which the electric furnace exhibits its great superiority over other modes of refining iron. During the period, the bath is almost completely deoxidized by means of carbon alone, and the removal of sulphur is positive and can be made almost complete. Its entire removal seems to be impracticable, as a content of less than .010 per cent. is obtained only after prolonged and expensive treatment. The flux added is, therefore, called either the desulphurizing or deoxidizing flux.

Oxygen: Oxygen occurs in steel principally as FeO, as has been stated in previous chapters, in which its harmful effects were also dwelt upon. Its removal may be represented by the following equation in which M may represent a great number of suitable elements:

$$FeO+M=MO+Fe.$$

The deoxidation may be brought about in the induction furnace only by means of the special deoxidizers previously noted, whereas in the Heroult furnace carbon alone may be employed. The use of carbon alone has been objected to because it was argued that the use of this element would give the oxide, CO, which is a gas, and the formation of this gas in the metal is objectionable. That steel at high temperature either combines with or dissolves this gas is fairly well established, for by experiment it has been shown that a given steel has a higher melting point in an atmosphere such as nitrogen than it has in an atmosphere of carbon monoxide. There is also good reason to believe that this gas is again liberated at certain temperatures on cooling. If this be true, then deoxidizing with carbon may give opportunity for the formation of blow holes and other defects in the ingots. Some metal, then, whose oxide is a solid that will easily come to the surface as slag is to be preferred for this purpose. This metal must not be volatile at high temperatures and must dissolve or alloy with the iron. The metals that best meet these requirements are the ferro-alloys of manganese, silicon, vanadium, titanium, and metallic aluminum. For many reasons, manganese, silicon and aluminum have proved the most satisfactory deoxidizers. How the carbon, acting through one or more of these elements, may be used to accomplish the deoxidation without injury to the steel is well illustrated by the practices at Duquesne and South Chicago Works, to be described later.

Removal of Sulphur: According to the statements of authorities upon the subject, sulphur may be removed in five ways: (1) As calcium sulphide, formed by the action of lime and carbon on ferrous sulphide at the high temperature of the arc furnace; (2) As calcium sulphide from the reaction of lime, ferrous sulphide, and calcium carbide at the higher

temperatures of the arc furnaces; (3) As calcium sulphide through the reaction of lime, ferrous sulphide, and silicon at the lower slag temperatures of the induction furnace; (4) As calcium sulphide through the reaction of calcium fluoride, ferrous sulphide, and silicon; (5) As iron sulphide from the action of ferrous oxide on calcium sulphide. The reactions illustrating the removal of sulphur in electric furnaces are as follows:

(1) $FeS+CaO+C=Fe+CaS+CO$. Occurs in arc furnaces only.

(2) $3\ FeS+2\ CaO+CaC_2=3\ Fe+3\ CaS+2\ CO$. In arc furnaces only.

(3) $2FeS+2CaO+Si=2Fe+2CaS+SiO_2$. Used with induction furnaces.

(4) $2CaF_2+2FeS+Si=2CaS+SiF_4+2Fe$. May occur in either induction or arc furnaces.

(5) $FeS+CaO \rightleftharpoons CaS+FeO$. May occur in arc furnaces.

An inspection of these reactions shows that certain requirements must be met before the elimination of sulphur can be brought about. Thus, in all cases a highly basic slag is essential, and in no case can desulphurization be effected before deoxidation of the metal and slag has been accomplished. The importance of the presence of elementary carbon or silicon is evident, and both these elements tend to react with iron or manganese oxides rather than with sulphides and lime. Furthermore, reaction (5) is reversible, acting from right to left in the presence of very slightly oxidizing influences. Because of the relation in concentration maintained between oxides in the metal and oxides in the slag, both deoxidation and desulphurization of the metal may be brought about by additions of carbon to the slag, if the temperature is sufficiently high. In arc furnaces this method is employed almost exclusively; but induction furnaces, owing to their lower temperatures, require that desulphurization be effected by the use of silicon, as shown in reactions (3) and (4), both of which take place at much lower temperatures than (1) and (2). In the arc furnace, complete deoxidation of metal and slag is recognized by the presence of calcium carbide in the slag.

The Finishing Period: With the dephosphorization and subsequent deoxidation of the bath, the contents of the furnace may be brought to a neutral or slightly reducing state, when the final additions may be made for finishing the steel to specifications. In order to save time, it is a common practice to make some additions before the desulphurizing period commences, especially if the additions are to be made in large quantities, which would chill the bath if added all at one time. As the conditions are reducing or neutral, loss of alloying elements is reduced to a minimum, and the composition of the steel can be controlled with comparative pre-

cision. The ability to finish the steel in the furnace gives the electric process another advantage over any of the older processes, also, as this practice tends to produce greater uniformity in the steel.

Some Comparisons: When deoxidation of the bath is complete, the contents of the electric furnace represents the nearest approach to perfect chemical equilibrium that has yet been attained in large metallurgical operations. In the converter and the open hearth, the metals are subjected to the action of air and gas; in the crucible, the metal takes up carbon and silicon; but in the electric furnace, the action of the metal on the basic lining being very slight, there is no exchange of elements between metal and slag, if traces of phosphorus be excepted.[1] Of course, if the dephosphorizing slag of the oxidizing period has not been completely removed before deoxidization begins, some of the phosphorus compounds in this slag, as well as some in the new slag, will be reduced. However, with careful watching, this gathering-up of phosphorus by the metal may be entirely avoided. As to the relative merits of the various types of electric furnaces, the results obtained are about equal. However, it is evident that arc furnaces are well suited for reducing processes, while induction furnaces lend themselves most readily to oxidizing purposes.

Fluxing Materials used in the electric furnace should be as pure as possible and free from injurious amounts of sulphur or phosphorus. The lime and fluorspar should not contain more than small amounts of magnesia, as it makes the slag less fusible, which fact is of great importance when the high basicity of the slags is considered. For recarburizing, a material low in volatile matter, phosphorus, and ash should be used. At Duquesne, anthracite coal is chiefly employed.

General Manufacturing Practice: As indicated previously, the electric furnace may be used to refine pig iron direct. But as the major portion of the refining may be accomplished much more cheaply by one of the older methods, direct refining is not economically practiced at present. Two courses of procedure, therefore, remain. In the one, cold scrap iron and steel of any grade as to quality is remelted and refined to produce steel of high quality, while in the other the electric furnace is made part of a duplexing process, whereby it is used in conjunction with one of the older methods of refining to produce superrefined plain steels or alloy steels. This second plan is the one used by the constituent companies of the U. S. Steel Corporation. At the South Chicago Works, the electric furnace is used in conjunction with Bessemer converters and tilting basic open hearth furnaces, and may be used in the finishing stage of either a duplex or a triplex process; but in most cases the steel finished in the electric furnace is taken from the open hearth. If Bessemer metal is used, it is first treated with an oxidizing slag to remove the phosphorus, then finished about as described in Section VIII. At Duquesne the duplexing

[1] Lyon and Keeney, Electric Furnaces for making Iron and Steel. Bureau of Mines Bulletin 67, Page 125.

is in connection with basic open hearths only, and to furnish a concrete example of the construction and workings of the electric furnace this plant will be described.

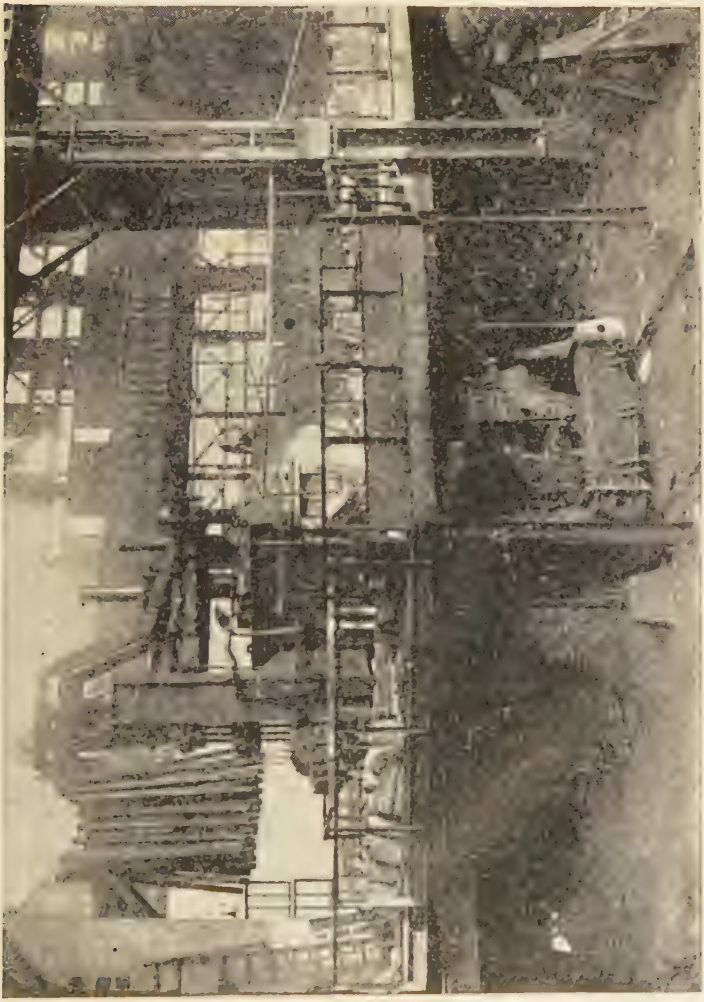


FIG. 104. Heroult Electric Furnace, General View—from Pouring Side.

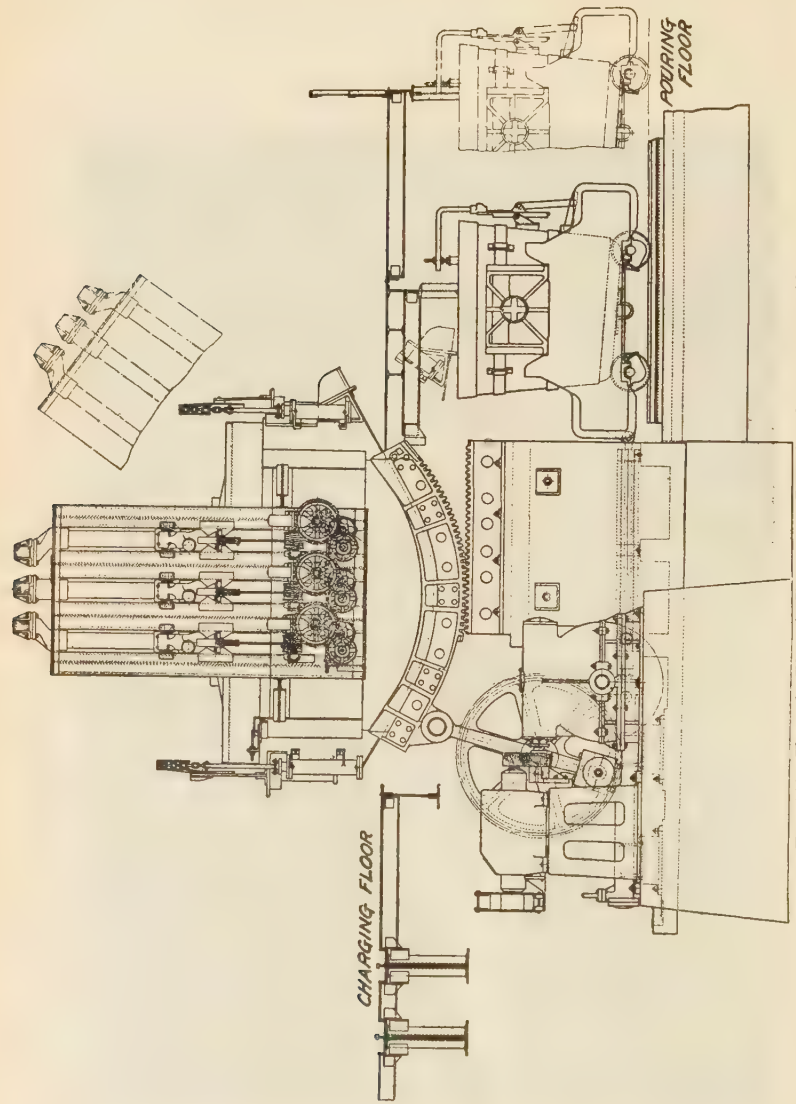


FIG. 105. Heroult Electric Furnace.—Drawing from Tower Side.

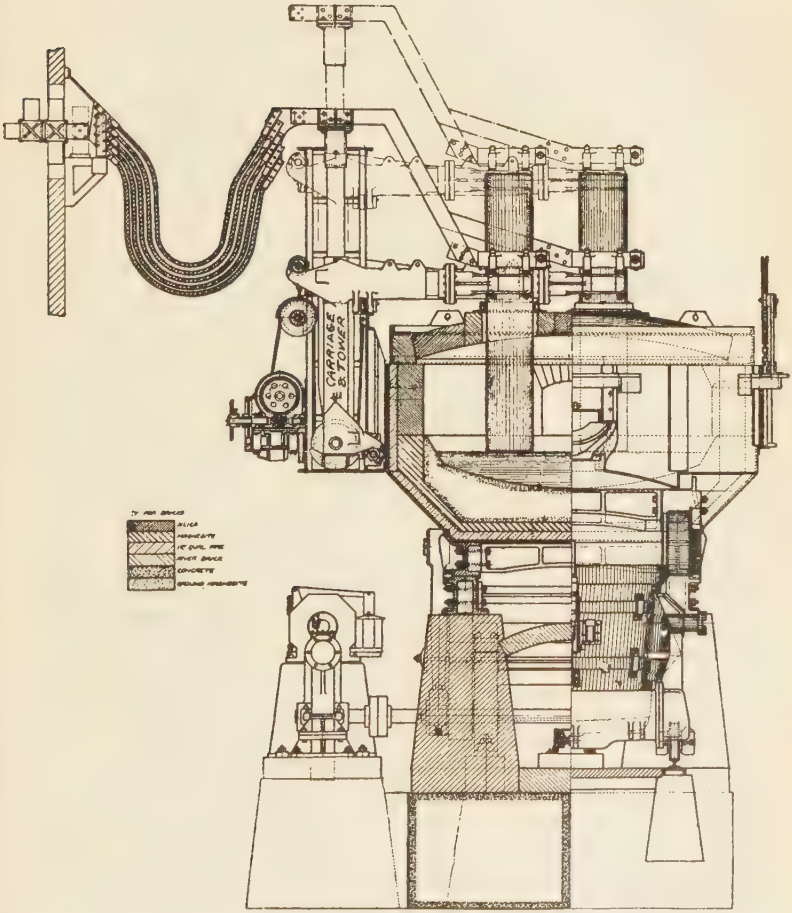


Fig. 106. Heroult Electric Furnace.—Vertical Section Through Tower and Furnace.

SECTION VII.

THE DUQUESNE PLANT—FEATURES PERTAINING TO ITS CONSTRUCTION.

Equipment: This plant was completed early in 1917, and is located at one end of No. 2 open hearth plant and in the same building. The special equipment of the plant may be said to consist of one 20-ton Heroult tilting furnace with a transformer station and testing laboratory, three charging ladles, three pouring ladles and one traveling over-head crane for charging. Other equipment such as teeming cranes, moulds, cars, etc. are part of the regular equipment of the open hearth plant. The open hearth floors are on two levels. The electric furnace, therefore, standing in line with the open hearths, is elevated and so constructed that it may be charged from the charging floor level, and tapped into the pouring ladle on the ground floor thirteen and one-half feet below the charging level. The transformer station is in a brick building just outside the open hearth building, and about eighteen feet from the center of the furnace. Three transformers are used, the combined capacity of which is 3500 K. W. From the transformers the current is conducted by means of bus bars to the corner of the transformer house nearest the pouring side of the furnace. Thence it is carried along a large number of heavy copper cables to the furnace. Wood bars, tied together like sections of a picket fence, are used to insulate the three lines of cables from each other. This arrangement furnishes the flexible connections necessary to permit the tilting of the furnace.

Construction of the Furnace Shell: The furnace is circular in form, and has an outside diameter of approximately sixteen feet. The shell is made of steel plates one inch thick, riveted together. This shell may be considered as being made in these three parts: A channelled band for the top, which is removable and made up of riveted plates; a side wall which is cylindrical in shape; and a bottom, which is shaped somewhat like a hopper. The bottom and side walls are riveted together. The shape of the bottom, front to back, is made to conform to heavy steel rockers, which rest on two heavy castings that serve as tracks. The rockers and tracks are provided with teeth, which mesh into each other and thus prevent the furnace from creeping. The weight of the furnace is supported by two brick piers upon which the tracks, or stationary racks, are bedded. The tops of these piers are about five feet above the ground. Attached to the rockers at the back of the furnace, are two crank shafts which in turn are connected to two large gear wheels, some five feet in diameter. These large wheels are geared to a 140 h. p. motor, which provides the power for tilting the furnace.

The Furnace Lining is made up of three layers of different materials. Next to the shell, in the bottom and sides, is placed a four and one-half-inch layer of fire brick laid edgewise, and upon this is laid a continuous bottom and side wall of magnesite brick. The bottom course is nine

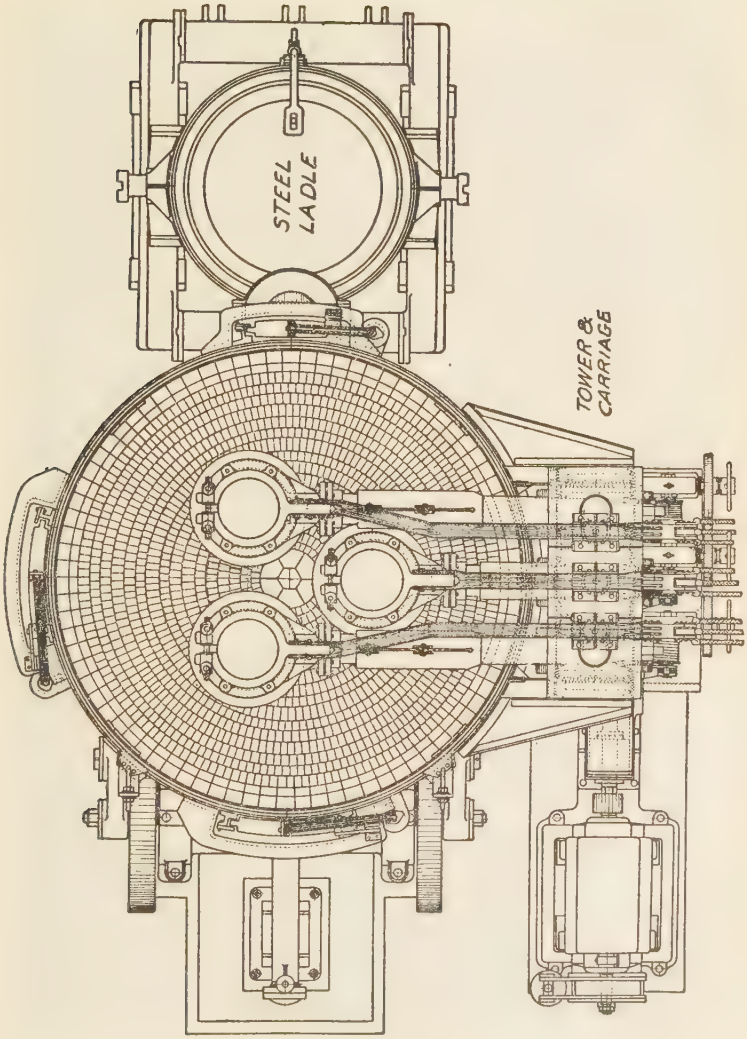


FIG. 107. Heroult Electric Furnace.—Perspective Drawing from Top

inches thick, while the side wall is thirteen and one-half inches in thickness. Upon the bottom brick is then sintered a layer, about thirteen inches thick, of dead burned magnesite, which is banked on the sides to a safe distance above the slag line.

The Roof is slightly dome-shaped, twelve inches in thickness and made of silica brick set in on end. The first course next the channelled band is made up of large skew-back brick. Thus, the roof is made self-supporting. As a roof lasts for forty to seventy heats only, two extras are held in reserve, ready to be placed in case a roof fails unexpectedly. In the roof, three openings are made for the electrodes. Each opening corresponds to one vertex of a equilateral triangle, each side of which is about six feet long, and the center of which is the center of the roof. When in place, the roof sets so that one vertex points toward the vertical guides for the electrodes, which are on the side of the furnace next the transformers. While in use, the top is bolted to four brackets on the shell to prevent the top from slipping when the furnace is tilted.

Controlling the Electrodes: Through the three openings, noted above, the electrodes extend into the furnace for a distance of about four feet. In order to make the electrodes adjustable, they are attached to horizontal arms that project out over the furnace from heavy vertical rods arranged to move up and down within vertical guides. At the top of these rods and properly insulated from them, the cables that carry the current from the transformer house to the furnace are bolted and welded to bus bars which lead to the electrode holders. Thus, the same motion is imparted to both the electrode holders and the bus bars. Each of these rods is supported and moved by means of a cable attached to its base and leading over a small drum geared to a small electric motor. These motors act through automatic regulators, which serve to keep the end of the electrode at the proper arcing distance from the bath. By reversing a switch on the switch board, these motors may be operated independently of the regulator. Furthermore, the lifting device is provided with a hand wheel, so as to be operated like a common windlass, whereby the electrodes may be regulated by hand.

The Electrode Holders are made in two parts, both of which are in the form of a two-pronged fork. The upper part is of copper and makes the connection between the electrodes and the bus bars, which are securely bolted to it. The electrodes are held between the two prongs, and since the distance between these prongs is about twenty-four inches, contact blocks must be used for electrodes less than twenty-four inches in diameter. A right-and-left screw bolt connects the ends of the two prongs, which enables the holder to be opened and closed at will and permits the electrode to be securely clamped in place. By this arrangement, electrodes of any size up to twenty-four inches diameter may be used. The lower part is made of steel and acts as a support for the upper part. These two parts, carefully insulated from each other, are held together by means of

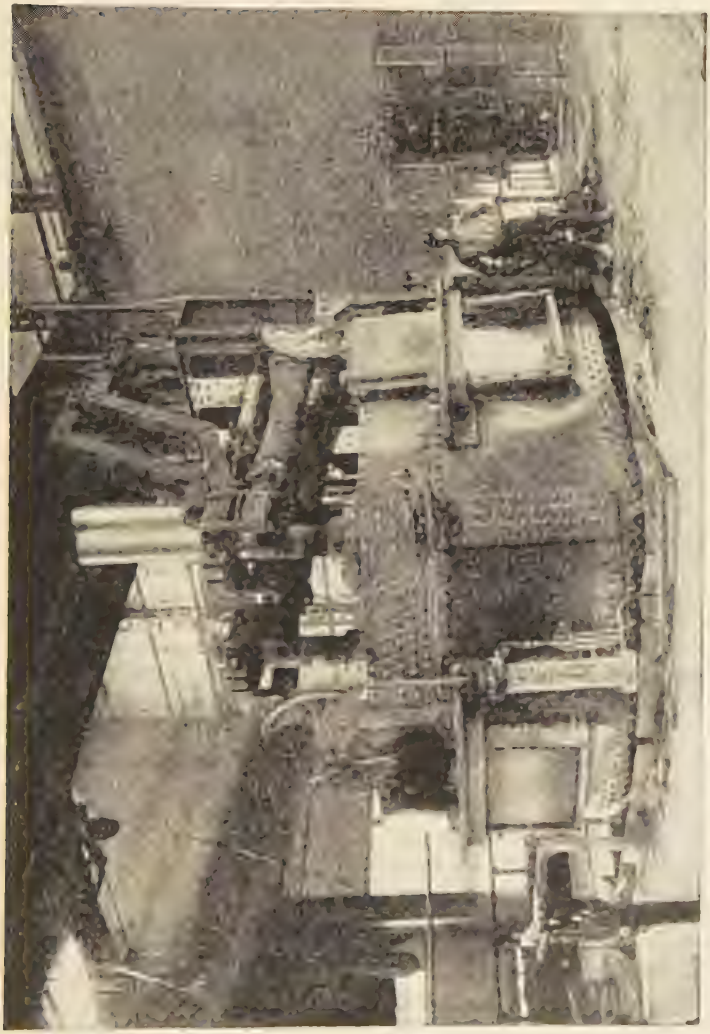


Fig. 188. Héroult Electric Furnace. General View—Furnace Ready to Charge.

insulated bolts. Finally, this lower part is fastened to the horizontal arm, previously mentioned, by an insulated flange joint. The upper prongs are water cooled.

The Electrodes used at the plant may be of graphite, twelve inches in diameter, or of amorphous carbon, twenty-four inches in diameter, and are received in sections six feet long. By means of threaded holes in the ends of the electrodes and headless screws of the same material to fit, these pieces may be joined together so as to give a continuous feed of electrodes to the furnace. In this way the great waste of electrodes from unused ends is avoided. These threaded holes also serve a useful purpose in removing the electrodes and changing them in the holders. As the carbons are constantly burning away, this change is frequently necessary. Since the electrodes are rather heavy—a six-foot length of graphite electrode weighs 426 lbs.—the use of the crane is made necessary. By means of a linked pin of steel, threaded to fit the hole, the electrodes can easily be handled with the crane hook. Experience seems to indicate that graphite electrodes are best for molten charges but that amorphous electrodes are very well suited for use in melting cold charges. A water cooled copper ring encircles each electrode at its entrance into the furnace.

Furnace Openings: Besides the holes in the roof for the three electrodes, the furnace has three openings in the side wall, all located within an arc of 180° on the circumference. One is the tapping hole, a small opening through which the steel is poured into the steel ladle. This opening is provided with a spout, so constructed as to act as a slag skimmer when the furnace is tapped. Opposite the tapping hole is the charging door, through which the molten metal from the open hearth is charged, while half way between these two openings is located a second charging door, which can be used only for charging solid materials by hand. Both these charging holes are closed with neat fitting brick lined doors, which are lifted by means of compressed air cylinders in much the same way as open hearth doors.

SECTION VIII.

OPERATION OF THE FURNACE.

Practice at Duquesne Plant: The Duquesne furnace is used to make plain steels of any carbon content and many different alloy steels. For all the steels made in the furnace the raw material charged is finished basic open hearth steel, hence the refining in the electric furnace consists of deoxidizing and desulphurizing only. Unless the specifications on the basic steel should coincide with those for the electric, which is seldom the case, additions are made to the charge either in the transfer ladle or in

the furnace. No additions of any kind are made in the pouring ladle or at the time of tapping, as is the common practice in making open hearth steel. A good example is furnished in the case of carbon. When it is necessary to raise the per cent. of this element, as is the case on orders calling for a higher per cent. than that of the open hearth heat, the amount required above that supplied by other additions is added, in the form of anthracite coal, to the steel in the transfer ladle, in the furnace, or a part in both. Additions of other elements are, as a rule, added after deoxidation of the metal is well advanced or completed. This ability to finish the heat in the furnace is a decided advantage in favor of the electric process, as a more homogeneous product is thus obtained.

Charging: Omitting the mechanical and electrical features, the operation of the furnace, in general, is carried out as follows:—Approximately twenty tons of a suitable open hearth heat is teemed from the steel ladle into the charging ladle for the electric furnace. This charge is then conveyed by a dinkey, over a narrow gauge track, to the furnace, into which it is poured through a portable spout. During the pouring, a test for chemical analysis is taken, and upon the results of this analysis is based the approximate amount of carbon and manganese to be added. An increase of three to five points in the manganese content of the steel usually occurs during the deoxidizing period, and must be allowed for. If a medium or high carbon heat is being made from a low carbon open hearth heat, requiring the addition of a large amount of carbon, the greater portion of this element is added in the form of anthracite coal, which is thrown into the furnace as the heat is being charged. This procedure is necessary to insure that the coal will be absorbed by the steel.

Deoxidizing: As soon as the charging has been completed, the electrodes are adjusted, and the current is turned on. Since the charge usually freezes over on top, especially in the case of low carbon steels, nothing further is done until this solidified layer is completely melted. As soon as the bath is in a state of complete fusion, the first slag mixture, consisting approximately of four parts lime and one part fluorspar or one part clean sand for low carbon heats, is added; for high carbon heats, the mixture may contain about one-third part coke dust. Soon after this addition, the second sample for chemical analysis is taken to determine the per cent. of carbon and manganese in the bath, and while these determinations are being made, further additions of the first slag mixture takes place. Samples of the slag taken at this time are usually brown in color and contain varying amounts of manganese oxide, which fact shows that the iron oxide in the steel is being reduced by the manganese present. A decided brown color can be taken to indicate that the deoxidation of the steel is well advanced. A second slag mixture composed of suitable proportions of lime, fluorspar, sand and coke dust is now added. Soon after the addition of this mixture the slag becomes less vitrious, shows a tendency to slake, and begins to

fade in color. If the heating be continued long enough, with proper additions of the carbonaceous flux, samples of the slag will slake when cold and become gray, or even white, in color. Such behavior of the slag indicates that the deoxidation of the bath of metal and slag has been completed. This condition is also determined by means of the water test. If at this time a small sample of the slag while hot be immersed in a little water, the odor of hydrogen sulphide can usually be detected, and, if deoxidation is complete, the smell of acetylene gas can also be detected.

Finishing the Heats: During the deoxidation of the bath, the results of the second chemical analysis have been reported, and if the per cents. of carbon and manganese are satisfactory, any alloys that may be required by the order are added as soon as the slag condition will permit. If the carbon content should be too low, it is raised to the required point by the addition of a proper weight of cold, very low phosphorus pig iron. The bath is chilled somewhat by the addition of the alloys, especially if they are added in large amounts, and about three-quarters of an hour is required to heat the bath up to the tapping temperature. Besides, in order to give the alloys time to mix with the steel, no additions are made for thirty minutes before tapping except in the case of 50-per cent. ferro-silicon, which is added ten to fifteen minutes before tapping to avoid losses of the element.

Tapping and Teeming: When enough time has elapsed to melt all the alloys or other additions, slaking and water tests are made on the slag, and if these indicate a satisfactory condition of the slag, the heat is tapped. In tapping the heats, care is taken to prevent slag from running into the steel ladle with the metal. The special skimmer with which the tapping hole is provided for this purpose has already been mentioned. The steel is teemed very carefully, being usually box poured. In this method of teeming the stream of molten metal from the ladle flows into the middle of a box made in three compartments. From the middle compartment the steel overflows into the two end ones, which are provided with nozzles. This arrangement permits these nozzles to be carefully centered over two ingot moulds before the pouring is begun. Special care is taken in preparing the ingot moulds, so as to prevent ingot defects due to bad moulds. The steel is allowed to stand in the moulds a sufficient length of time to insure that solidification is complete before it is stripped.

Scrap Heats: Besides the refining of molten open hearth steel, which has just been described, the furnace is occasionally used to make steel from scrap. When using scrap, two methods may be followed. Thus the charge may consist of cold scrap or be made up of scrap and molten steel. When scrap alone is used, it must be small, and the coarser material is charged first with the finest on the top. Even then the power fluctuations are great, and some difficulty is experienced in melting the scrap. These

difficulties are overcome for the most part by starting the furnace on a short charge of molten steel and then adding the scrap to this charge. This latter method is the one employed most often at this plant. After the melting period the procedure is then the same as that already described for molten charges. An examination of the following tables will give a more concrete idea of the method of handling the different kinds of steel made in the electric furnace.

Table 47. Showing History of a Heat of Low Carbon Plain Steel Made in the Electric Furnace.

Analysis of molten charge—steel as finished at open hearth: C.=.09%; Mn.=.38%; P.=.014%; S=.043%.

Order: C. .10/.15%; Mn.=.30/.50%; P. under .035%; S. under .040%; Si. under .04%.

Time	Additions
8:10	Charge, 46700 lbs. Test. C.=.06%; Mn.=.33%; P.=.010%; S.=.038%.
8:35	Power on.
9:35	1st slag mixture. Lime, 500 lbs., fluorspar, 150 lbs.
9:50	485 lbs. pig iron added.
10:00	½ second slag mixture, Lime, 750 Lbs., fluorspar, 125 lbs., coke dust, 100 lbs; sand, 100 lbs.
10:05	Sample for chemical analysis.
10:20	104 lbs. ferro-manganese added cold. (Laboratory report shows C.=.08%; Mn.=.19%.)
10:30	Chemical analysis, C.=.10%; Mn.=.32%.
10:45	50 lbs. Ferro-manganese added cold.
10:50	300 lbs. pig iron added cold.
10:55	½ second slag mixture.
11:00	¼ third slag mixture—Lime, 100 lbs.; fluorspar, 30 lbs.; coke dust, 75 lbs.
11:30	¼ third slag mixture.
11:40	¼ third slag mixture.
11:45	¼ third slag mixture.
12:00	20 lbs. coke dust.
12:30	30 lbs. coke dust.
12:35	50 lbs. ferro-manganese added cold.
12:50	Heat tapped.

Final analysis: C.=.12%; Mn.=.35%; P.=.007%; S.=.035%; Si.=.01%.

Table 48. A Heat of High Carbon Plain Steel.

Molten charge—Steel as finished at open hearth—C.=.19%; Mn.=.28%; P.=.016%; S.=.041%.

Order: C.=.95/1.05%; Mn.=.20/.35%; P.=under .030%; S.=under .030%; Si.=.10/.25%.

Time	Additions
3:20	150 lbs. Anthracite Coal added to ladle.
3:30	Charge, 52400 lbs. Test: C.=.29%; Mn.=.23%; P.=.012%; S.=.042%.
	660 lbs. Coal added in furnace as heat is being charged.
3:35	155 lbs. coal added.
3:40	Power on.
5:35	½ first slag mixture. Lime, 1200 lbs.; fluorspar, 200 lbs.; coke dust, 100 lbs; sand, 100 lbs.
6:15	Chemical Analysis { front door, —C.=.85%; Mn.=.29%. side door, —C.=.85%; Mn.=.28%.
6:15	¼ first slag mixture.
6:30	⅛ first slag mixture.
6:40	1/16 first slag mixture.
6:50	1/16 first slag mixture.
7:00	⅓ second slag mixture. Lime, 100 lbs.; fluorspar, 25 lbs.; coke dust, 75 lbs.
7:05	1700 lbs. pig iron.
7:10	⅓ second slag mixture.
7:15	⅓ second slag mixture.
7:20	175 lbs. 50% ferro-silicon.
7:40	Power off, and heat tapped.

Final analysis, C.=.97%; Mn.=.29%; P.=.007%; S.=.016%; Si.=.19%.

Table 49. A Low Carbon Alloy Heat.

Molten Charge as finished at Open Hearth, C.=.09%; Mn.=.34%; P.=.015%; S.=.034%.

Order: C.=.12/.20%; Mn.=.40/.70%; P.=under .040%; S.=under .040%; Si.=under .20%; Cr.=.40/.80%; Ni.=1.00/1.75%.

Time	Additions
10:55	Charge, 50800 lbs. Test, C.=.08%; Mn.=.29%; P.=.010%; S.=.042%.
11:15	Power on.
12:00	First slag mixture. Lime, 500 lbs.; fluorspar, 150 lbs.;
12:30	¾ second slag mixture. Lime, 750 lbs.; fluorspar, 125 lbs.; coke dust, 100 lbs; sand, 100 lbs.
12:45	Chemical Analysis { front door, C.=.08%; Mn.=.24%. side door, C.=.08%; Mn.=.22%.
12:50	200 lbs. ferro-manganese; Mn.=78%.
12:55	446 lbs. ferro-chrome; Cr.=70%.
1:00	730 lbs. nickel; Ni.=99%.
1:30	½ third slag mixture—Lime, 50 lbs.; coke dust, 75 lbs.
1:45	½ third slag mixture.
1:50	30 lbs. ferro-manganese and 60 lbs. 50% ferro-silicon.
2:00	Heat tapped.

Final Analysis, C.=.20%; Mn.=.51%; P.=.009%; S.=.028%; Si.=.03%; Cr.=.54%; Ni.=1.28%.

Table 50. A High Carbon Alloy Heat.

Molten charge—Steel as finished at open hearth—C.=.20%; Mn.=.35%; P.=.010%; S.=.035%.

Order: C.=.95/1.05%; Mn.=.35/.50%; P.=under .030%; S.=under .030%; Si.=under .03%; Cr.=1.35/1.65%; V.=over .18%.

Time	Additions
11:48	150 lbs. anthracite coal added in transfer ladle.
11:50	Charge, 54500 lbs. Test, C.=.37%; Mn.=.34%; P.=.006%; S.=.040%. 650 lbs. coal added as heat is charged,
12:05	Power on.
12:50	¾ first slag mixture—Lime, 1300 lbs.; fluorspar, 160 lbs; sand, 125 lbs.
1:20	Chemical analysis {Front door, C.=.89%; Mn.=.34%. Side door, C.=.90%; Mn.=.35%.
1:25	¼ slag mixture.
1:35	⅙ second slag mixture. Lime, 150 lbs.; coke dust, 150 lbs.
2:00	1180 lbs. ferro-chrome, Cr.=70%.
2:10 to 2:40	Remainder of second slag mixture added at intervals of ten minutes.
2:55	353 lbs. ferro-vanadium. V.=35%
3:05	60 lbs., 50-per cent. ferro-silicon.
3:30	Heat tapped.

Final analysis, C.=.99%; Mn.=.35%; P.=.006%; S.=.017%; Si.=.07%; Cr.=1.44%; V.=.22%.

SECTION IX.

THE CHEMISTRY OF THE PROCESS.

Deoxidation of the Bath: The tracing of the chemical changes that take place in the process employed at this plant furnishes an interesting study. Since the charge is finished open hearth steel containing the usual amount of manganese, it is to be expected that this element would play a most important part in the deoxidation of the steel. The fact, plainly shown by the preceding records, that the manganese is usually several points lower in the charging test than in the open hearth steel is proof of its deoxidizing action, which would be expected to continue in the furnace. The removal of oxygen, then, is represented by the following reaction: $FeO+Mn=MnO+Fe$. The MnO, being less soluble in the molten metal than FeO, rises to the surface and becomes a part of the slag. This action is identical with that in the ladle in finishing open hearth steel, but the result is not the same in the two processes for two reasons: First, for want of time, the deoxidation is not completed in the ladle, whereas in the electric furnace it is complete. Second, the MnO in the electric furnace comes under the reducing action of the carbon contained in the slag mixture and is reduced, thus: $MnO+C=Mn+CO$. The carbon monoxide, CO, being a gas, becomes a part of the atmosphere of the furnace, and the manganese returns to the bath, as is indicated by the fact that the per cent. manganese in the steel usually rises after the addition of the carbonaceous flux.

Desulphurizing the Metal: With the elimination of oxides from the slag, the lime, under the influence of the extremely high temperature of the arc which prevails under and in the immediate vicinity of the electrodes, begins to be reduced by the carbon of the coke dust, with the consequent formation of calcium carbide, thus: $CaO+3C=CaC_2+CO$. It is at this point that desulphurization takes place. Since manganese sulphide, like the oxide, is less soluble in iron than ferrous sulphide, it is probable that this element also aids in this process. Whether manganese sulphide or ferrous sulphide plays the most important role in the sulphur reactions is difficult to decide, but that the removal of the sulphur from the bath takes place through the formation of calcium sulphide, which is insoluble in molten iron, cannot be doubted. These reactions are two in number and may be written thus:

$$1.\quad \begin{Bmatrix} FeS \\ MnS \end{Bmatrix} + CaO + C = \begin{Bmatrix} Fe \\ Mn \end{Bmatrix} + CaS + CO$$

$$2.\quad \begin{Bmatrix} 3\,FeS \\ 3\,MnS \end{Bmatrix} + 2\,CaO + CaC_2 = \begin{Bmatrix} 3\,Fe \\ 3\,Mn \end{Bmatrix} + 3CaS + 2\,CO$$

With metallic oxides present in the slag, neither of these reactions will take place, as the oxide would react with the calcium sulphide, thus:

$$CaS+\begin{cases}FeO\\MnO\end{cases}=\begin{cases}FeS\\MnS\end{cases}+CaO$$

and with calcium carbide according to this reaction:

$$CaC_2+\begin{cases}3\ FeO\\3\ MnO\end{cases}=\begin{cases}3\ Fe\\3\ Mn\end{cases}+CaO+2\ CO$$

Hence the presence of CaC_2 in the slag is a guarantee that the bath is deoxidized. In the water test the presence of considerable quantities of CaC_2 in the slag is detected by the odor of acetylene gas, which is generated in accordance with the following reaction: $CaC_2+H_2O=C_2H_2+CaO$. These facts are further illustrated by the following analysis of heats and slags: Slags AZ No. 3 and AZ No. 5 illustrate an undesirable and a desirable slag, respectively. The relatively high iron and manganese content of AZ No. 3 indicate incomplete deoxidation, with a low sulphur and calcium carbide content resulting.

Table 51. Analysis of Tests from Electric Furnace Heats.

Heat Number	Tests	Carbon %	Mang. %	Phos. %	Sul. %	Si. %
AZ No. 1, (O. H. Heat 83023)	Primary	.16	.35	.010	.036	..
	1st Preliminary	.80	.35	.006	.023	..
	2d "	.80	...	....	....	..
	Final	.82	.35	.010	.020	.16
AZ No. 2, (O. H. Heat 88026)	Primary	.20	.44	.012	.042	..
	Preliminary	.61	.43	.010	.025	..
	Final	.67	.60	.009	.024	..
AZ No. 3, (O. H. Heat 84598)	Charging	.18	.41	.005	.024	..
	No. 1 Electrode	.20	.60	.004	.020	..
	No. 2 "	.19	.60	.006	.020	..
	No. 3 "	.21	.59	.005	.020	..
	Final	.22	.58	.004	.021	..
AZ No. 4, (O. H. Heat 101523)	Charging	.19	.34	.010	.032	..
	No. 1 Electrode	.22	.53	.007	.026	..
	No. 2 "	.22	.54	.009	.023	..
	No. 3 "	.22	.54	.009	.023	..
	Final	.20	.47	.006	.029	..
AZ No. 5, (O. H. Heat 101524)	Charging	.28	.36	.009	.040	..
	No. 1 Electrode	.34	.54	.007	.017	..
	No. 2 "	.32	.55	.006	.015	..
	Final	.33	.52	.007	.020	..

Table 52. Partial Analysis of Final Electric Furnace Slags.

Heat Nos.	AZ No. 3	AZ No. 4	AZ No. 5
Silica	19.58%	20.48%	18.40%
Iron	1.09	.72	.32
Total Lime	60.38	61.82	61.26
Magnesia	10.32	8.40	7.27
Manganese	.62	.60	.35
Sulphur	.85	.80	1.30
Calcium carbide	.32	.19	.46
Alumina	3.04	3.61	5.95

Difficult Specifications: While the electric furnace affords means of making steel to very difficult specifications and with a greater degree of accuracy than is possible in other processes, yet it has its limitations. The case of sulphur furnishes an example. From what has just been said, the importance of carbon in the elimination of both oxygen and sulphur is evident. In low carbon steels the lowering of the sulphur content to any considerable degree becomes a difficult problem, because, if the flux be made highly carbonaceous, a necessary condition, there is danger that the steel will absorb carbon from the slag, and thus raise the carbon content of the steel above the requirements. In the high carbon steels, the absorption of carbon by the steel can be allowed for and presents no difficulty, so a more highly carbonaceous flux may be used than with low carbons, and a greater removal of sulphur results. As previously indicated, the elimination of sulphur may be brought about by the use of silicon, as shown in the following reactions:

$$1.\quad \begin{Bmatrix} 2\ FeS \\ 2\ MnS \end{Bmatrix} + 2\ CaO + Si = \begin{Bmatrix} 2\ Fe \\ 2\ Mn \end{Bmatrix} + 2\ CaS + SiO_2$$

$$2.\quad \begin{Bmatrix} 2\ FeS \\ 2\ MnS \end{Bmatrix} + 2\ CaF_2 + Si = \begin{Bmatrix} 2\ Fe \\ 2\ Mn \end{Bmatrix} + 2\ CaS + SiF_4$$

But while it is claimed that little more than the theoretical amount of silicon is required, in actual practice a residue of silicon in the steel is unavoidable. Hence, this method could not be employed to produce silicon-free steel. Similar to the method of desulphurizing with carbon, these reactions will take place only after the bath has been completely deoxidized. For low carbon steels, then, the limit for sulphur should be .040 per cent., while for high carbons this limit could be reduced to .030 per cent. To guarantee lower limits than these would mean increased cost in production out of proportion to the benefits to be derived, except in the case of steel that is to be used for certain special purposes. Since the phosphorus is removed in the basic open hearth, the same range in per cent. of this element as is customary to allow in open hearth steel should be allowed in electric steel. As to alloying elements, the variation in the composition of the alloys used makes it desirable to secure as wide a range as possible in the specifications for such elements.

SECTION X.

PROPERTIES AND USES OF ELECTRIC STEEL.

Properties of Electric Steel: We can deal with this topic in a no more fitting way than to quote from impartial investigators. The following is taken from a paper by Messrs. Lyon and Keeney of the Bureau of Mines:

"For many years all high grade steels were manufactured by the crucible process, but since the advent of the electric furnace there has been a gradual adoption of that furnace for refining steel. For the complete refining of the highest grades of steel the use of the electric furnace is now thoroughly established. Any products that can be made by the crucible process can be made by the electric furnace, and in most cases with cheaper raw materials and at a low cost. In the electric furnace complex alloy steels can be made with precision. The high temperatures attainable facilitate the reactions, and alloys need not be used so largely for the purpose of removing gas. Very low carbon steels can be kept fluid at the high temperatures. Steels free from impurities and of great value for electrical apparatus can be made. With the electric furnace large castings can be made from one furnace, whereas in the crucible process steel from several crucibles must be used. For small castings, which require a very high grade metal free from slags and oxides, electrically refined steel is especially adapted. The electric furnace gives a metal of low or high carbon content as desired, hot enough to pour into thin moulds, and steel free from slags and gases."

"There is now a tendency among customers of rail and structural steel to require a higher grade steel at an increased price rather than steel of acid Bessemer or even of basic open hearth grade at a lower price. With the high cost of power that now prevails throughout the steel centers of the United States the electric furnace can not compete profitably with either the acid Bessemer or the basic open hearth process in manufacturing steel of like grade from pig iron. It is in combination with either of these processes that the electric furnace seems destined to be prominent in steel manufacture."

"Experiments conducted by the United States Steel Corporation during the past four years show that, as compared with the acid Bessemer and basic open hearth processes, the electric process has the following advantages: A more complete removal of oxygen; the absence of oxides caused by the addition of silicon, manganese, etc;—the production of steel ingots of 8 tons weight and smaller that are practically free from segregation; reduction of the sulphur content to 0.005 per cent., if desired; reduction of the phosphorus content to .005 per cent. as in the basic open hearth process, but with complete removal of oxygen."

"About 5,600 tons of standard electric rails from electric furnace steel have been in service in the United States for the past two years (prior to 1914). These rails have been subjected to all sorts of weather and to temperatures as low as—52° F. It seems that rails made by the basic electric process can be made softer than by either the acid Bessemer or basic open hearth processes and yet show highly satisfactory wearing qualities."

"No steel rails made by the basic electric process in service in this country have been broken. Electric furnace steel of a given tensile strength has a slightly greater elongation than basic open hearth steel and is somewhat denser than basic open hearth or acid Bessemer steel."

The results of some comparative tests, made at South Chicago of electric furnace steel for plates and basic open hearth steel for plates were as follows:—

Table 53. Comparison of Mechanical Properties of Electric and Open Hearth Plate Steel.

ELECTRIC			OPEN HEARTH		
Carbon Content Per Cent.	Ultimate Strength per Sq. In. Pounds	Elongation on 2 Inches Per Cent.	Carbon Content Per Cent.	Ultimate Strength per Sq. In. Pounds	Elongation on 2 Inches Per Cent.
0.08	59,194	27.25	0.08	51,690	32.00
.12	64,080	26.05	.12	56,510	29.70
.16	69,220	25.25	.16	52,901	28.61
.20	72,853	22.82	.20	58,294	28.82
.24	69,540	23.12	.24	63,560	26.25

The results show a 15.5-per cent. increase in ultimate strength and 11.3-per cent. decrease in elongation for electric steel, as compared with open hearth plate steel of approximately the same chemical composition.

Illinois Steel Company's Tests on Rails: The Illinois Steel Company have conducted a series of experiments from which it was shown that electric steel is considerably more ductile at low temperatures than either the open hearth or the Bessemer steel. In these tests about 900 pieces of electric, open hearth, and Bessemer rails were tested at temperatures ranging from 70° F. to —50° F., and the results indicated that while all these steels showed a marked decrease in resistance to shock as the temperature was lowered, the electric steel was relatively more ductile than either of the other two. The following table is a summary of the results obtained with

two open hearth and two electric heats of similar composition chemically, as shown by analysis, and may be taken as typical of the general results obtained.

Table 54. Comparison of Tests on Open Hearth and Electric Steel Railroad Rails at Different Temperatures.
Number of Tests, 242.

Temp. Deg's F.	AVG. No. BLOWS TO BREAK RAILS				DEFLECTION BEFORE BREAKING				ELONGATION IN 12 IN.			
	Elec.	O. H.	Comparison		Elec.	O. H.	Comparison		Elec.	O. H.	Comparison	
			O. H. Over E.	E. Over O. H.	Inches	Inches	O. H. Over E.	E. Over O. H.	Inches	Inches	O. H. Over E.	E. Over O. H.
+60	3.48	3.64	5%	.....	2.96	3.36	14%	.....	.808	.929	15%	.....
0	4.41	3.82	...	15%	1.41	1.23	....	15%	.404	.397	....	2%
—30	4.55	2.24	...	103%	1.46	.58	....	152%	.420	.201	....	109%
—40	3.31	2.03	...	65%	.91	.43	....	112%	.297	.141	....	111%

Uses of Electric Steel: As to the uses of electric steel, little need be said except it may be used with confidence wherever a steel of higher quality than that furnished by the open hearth process is desirable. So far, the demand for this steel has been in advance of the supply, and its application is becoming more and more general. Among those with whom it has found favor and by whom it is now being used, are manufacturers of automobiles, motorcycles, motor accessories, airplanes, machinery, engines, agricultural implements, tools, guns and munitions, and by the railroads. The fact that it is being used more and more in place of crucible steel is evidence of its superior quality.

Summary: In order to cover the whole subject of electric steel making satisfactorily in so brief a manner, it has been necessary to treat the subject from several different view points, which method is likely to be confusing, with the result that the reader may have lost sight of some important points. In order that these points may receive proper emphasis, the following summary of the chapter is appended:

1. Of the many furnaces in use no one can be said to possess any great advantage over any other from a metallurgical point of view, with the exception that higher temperatures may be obtained with furnaces of the arc type than with the induction type.

2. The only effect of the electric current is in the production of heat.

3. The electric process is the only one in which impurities are not added to the steel by the operations.

4. The electro-thermal process affords the only positive means of desulphurizing and deoxidizing steel simultaneously and in the same operation.

5. It permits the addition of all alloying elements while the steel is in the furnace.

6. It provides a way for remelting alloy steel scrap and producing a product of high quality without loss.

7. Steel produced by this process exhibits some unusual wearing qualities.

8. In quality, steel properly made by this process equals that of the best grades of crucible steel.

9. Much larger quantities of metal may be treated in one operation than is possible by the crucible process.

10. It gives a product that is uniform in quality for any given heat.

11. Steels refined in the electric furnace and properly cast are freest from segregation.

12. Steels may be made by the electric process comparatively free from slag and other inclusions.

13. Electric steel is more ductile at low temperatures than Bessemer or open hearth.

14. Considering the various methods from an economical point of view, the duplexing process in which the electric furnace is used in conjunction with the basic open hearth combines the greatest capacity and efficiency with highest quality of product.

CHAPTER XII.

THE DUPLEX AND TRIPLEX PROCESSES.

SECTION I.

GENERAL FEATURES OF THE DUPLEX PROCESS.

What the Duplex Process Is: The term duplex process may be applied to a combination of any two processes for manufacturing steel, but it is customary among the steel men of this country, at least, to restrict the term to mean only a combination of the acid Bessemer and the basic open hearth process, in which the latter plays the part of a finishing process. Briefly described, the method, as usually carried out, consists, first, of blowing molten basic iron in the converter until the silicon, manganese and a part of the carbon have been oxidized, and then transferring this semi-finished metal to a basic open hearth furnace, where, through the agencies of iron oxide and lime, the phosphorus and the remainder of the carbon to be removed are oxidized. The steel is then finished, recarburized and deoxidized, according to the usual open hearth practice. This combination of processes may be made in other ways, also. One plant, for example, in order to produce a very low phosphorus Bessemer steel for a certain order, first oxidized the silicon, manganese, and phosphorus in the open hearth, and then, by mixing this very high carbon steel with Bessemer iron in suitable proportions, succeeded in blowing out the carbon in the converter, thus reversing the customary procedure. But as stated in the beginning, the duplex process refers to the combination in which the finishing operation is conducted in and from a basic open hearth furnace.

Advantages and Disadvantages of the Process: In the northern district of the United States the chief advantages of the process, when there is a pressing demand for steel, is that of the increased tonnage which it produces in a given time. Thus, while the product is similar in quality and of the same grades as basic steel, the time of the open hearth operation is shortened by about half; for, whereas one open hearth furnace will turn out an average of about fifteen heats in a week of straight running by the ordinary way, the same furnace operated as a duplexing unit will produce about forty heats in the same period. This shortening of the time of a heat saves fuel and tends to prolong the life of the furnace, as does, also, the elimination of the silicon in the converter. The process does not require the use of scrap, which fact may also be an advantage to some makers. Offsetting these advantages, however, are the double conversion cost and the decrease in yield, due to the increased oxidation, both of which may be very serious drawbacks to the economical production of steel. In dull

times, especially, the extra costs of maintaining two separate units may more than counter-balance the gain from the increased output.

Methods of Duplexing: While the details of the process vary widely in the different plants, there are two general methods of carrying out the duplexing process: Thus, the purification in the converter may be carried out to the point where the metal is fully blown and represents a high phosphorus steel which may then be mixed with pig iron in the open hearth, thus taking the place of steel scrap. In this method either a stationary or a tilting furnace can be utilized. But the more common method is the one, already mentioned, in which the carbon is only partially eliminated in the converter, and the purification then completed by the continuous process, which is most conveniently carried out in a Talbot tilting furnace. A brief description of these furnaces will simplify the description of the process to be given shortly.

The Talbot Furnace: The object aimed at in the design of these furnaces is to permit the removal of any quantity of slag or metal or the addition of molten metal, oxidizing agents and flux at any time during the working of the charge. They are, therefore, necessarily of the tilting type, and are built upon racers and rollers which rest upon the foundation in a manner similar, in a general way, to that of the large mixers of recent construction. They are rectangular in shape, and of about the same proportions as an ordinary open hearth furnace as to length and width,but they have a much greater depth, which increases their capacity for containing molten metal. The frame work must be of much stronger construction than that for the ordinary open hearth in order to avoid twisting stresses and vibrations which would be very harmful to the brick work. Only that section of the furnace comprising the hearth, side-walls and roof is made tilting; all the ports and flues are stationary, and, together with the checker work, of the same construction as for the stationary furnaces. In the best types of construction, these furnaces are so placed and the racers and rollers so formed that the center of rotation of the furnace coincides with the center line of the ports, so that all its parts always remain in the same relation no matter in what direction or to what degree the movable portion of the furnace may be tilted. By means of water cooled metal joints, the clearance between the movable and stationary parts of the ports is kept very small, so that the heating of the furnace may continue even during the tapping of a heat. On the pouring side, these furnaces usually have but one opening, a tapping hole located above the slag line and provided with a lip or spout for directing the stream of molten metal into the steel ladle. As in the case of the stationary furnace, doors for introducing the materials into the furnace are located in the front side. But unlike the stationary types, the slag notches are also placed in front, usually one on each side of the middle door, and, of course, at a lower level. Since Talbot's method is but a modification of the basic open hearth process, the furnaces are, as a matter of course, provided with basic linings.

SECTION II.

OPERATION OF THE PROCESS.

An Example of the Duplexing Process: Perhaps the best way to describe the duplexing process is through an example. For this purpose the method employed by a large steel manufacturing company in the North, whose plant represents one of the most recent installations, is selected. Their duplexing plant consists of three 20-ton converters and three Talbot tilting furnaces, each of which has a capacity of approximately 200 tons. While the practice may be varied somewhat to suit conditions, the process at this plant is usually carried out about as follows:

Preparing the Furnace for Charging: The process may be said to be continuous for a week, for each week-end the tilting furnace is thoroughly drained, the bottom and slag lines are made up, the ports are cleaned and repaired, and everything is made ready for the week's campaign. Of course, during the interval of this campaign, the front and back wall must be attended to and such minor repairs made as are found necessary and there is time for. About 6 p. m. Sunday, after the flues have been burned out and the gas is once more on the furnace, the work of preparing the slag is begun. Four boxes of calcined limestone and three of roll scale are charged and melted down. These amounts are then repeated, and when again molten the same amounts are again charged, the total being about twelve boxes of lime and eight to nine boxes of roll scale. The average weight of a box of the lime is 2000 lbs. and of a box of roll scale, 3000 lbs. Considerable care is given by the melter to the preparation of a good slag, for, as in all open hearth work, the success of the process depends on the slag.

Charging Molten Metal from the Converters for the First Heat: At midnight, or shortly afterwards, the metal is ordered from the Bessemer department. An average analysis of the mixer metal is as follows:

Total Carbon	3.85 per cent.
Silicon	1.55 "
Manganese	.67 "
Sulphur	.040 "
Phosphorus	.365 "

The weight of this metal taken for a Bessemer heat is about 40,000 lbs., less the weight of the scrap in the converter. Two Bessemer heats, blown in different vessels, are poured into a transfer ladle and taken to the tilting furnace. When starting up, the first ladle contains metal blown down to contain 0.60 per cent. carbon, which is allowed to remain to give a little action, or boil, in the furnace. This first ladle is poured into the open hearth furnace about midnight. It is followed by a ladle of "soft" metal, that is, metal blown down to 0.05 per cent. or 0.07 per cent. carbon, and

then by a "kicker," or a ladle of high carbon steel. This metal is blown down to from 1.5 per cent. to 2.0 per cent. carbon, and when charged into the open hearth produces a vigorous reaction, or boil. The metal and slag are thoroughly mixed together by this boil, and during this reaction the phosphorus is largely removed from the metal bath, and passes into the slag. When the action has subsided, another "soft" ladle and a "kicker" are charged. Then, if the bath is found to be low in carbon, another kicker ladle is added to it, but if high in carbon another "soft" ladle is charged. In this way a bath of metal of about 200 tons is produced. The charge is then worked down like an ordinary basic open hearth heat until ready for tapping, which is usually at about 3:30 a. m.

Tapping and Recarburizing the First Heat: When the bath is ready for tapping, the tap hole is opened and plugged with wet sacking. The furnace is then tilted for pouring. Before the sacking is burnt through, the slag is up along the back wall above the tapping hole, so that clean metal free from slag comes from the furnace. Only enough slag is drawn off at the end to cover the steel in the ladle properly. Some of the steel made in the Talbot furnaces is superrefined by the electric process, but by far the greater portion is made into the ordinary commercial grades which is recarburized and deoxidized in the ladle as for similar grades made in stationary furnaces.

Preparing the Furnace for the Second Heat: After the first heat is tapped, there is a bath of about 100 tons of metal with a carbon content of about .15 per cent. still in the furnace, covered with the tapping slag. Two boxes of lime and two boxes of scale are charged, and two boxes of burnt dolomite are used along the slag line, around the doors, etc., as found necessary. Then two "soft" ladles of blown metal are charged, and two more boxes of lime, which is followed by a "kicker." During the reaction, the furnace is tilted slightly forward and slag is allowed to flow from the front of the furnace through the slag spouts, which are under the doors directly on each side of the center door. The slag falls into slag cars standing on the tracks below. Practically all the slag taken from the furnace is removed in this way, for, as mentioned before, when tapping a heat only enough is taken to cover the metal in the ladle properly. When the reaction is over, another box of lime is generally charged, and the bath is worked down in the usual way. Very often, another box of lime is spread over the slag shortly before tapping, so that five to six boxes of lime are used per heat, but as a rule only two boxes of scale are used here. After the heat is tapped, this procedure is repeated, enough slag being taken from the front of the furnace at the time of the reaction to maintain a constant and proper volume of slag in the furnace. The average time for tapping one heat to tapping the next is about three hours.

Closing Down the Furnace for the Week-End: About midnight on Saturday the furnace is drained. The bath is worked down, so that after the heat is tapped there are not more than forty to sixty tons in the furnace. Then this residue of metal is tapped and made into soft steel, for which there is a constant demand, by making the proper additions of ferro-manganese and recarburizer.

The Slag: At the high temperature at which its removal is effected, phosphorus is easily reduced, so in order to oxidize, flux and hold the phosphorus in the open hearth slag, it is necessary that the latter be very basic and highly oxidizing, as an analysis shows. The average composition of the slag is about as follows: Silica, SiO_2, 6.35%; ferrous oxide, FeO, 21.65%; ferric oxide, Fe_2O_3, 6.90%; manganese, Mn, 1.12%; phosphorus, P, 3.25%; alumina, Al_2O_3, .97%; lime, CaO, 44.07%; magnesia, MgO, 8.04%. The high percentage of iron oxides, which are equivalent to approximately 24.0 per cent. metallic iron, gives the impression that the process is wasteful of iron, which is true, but due to another cause. While the percentage of iron oxide is high, it does not exceed that of the run-off slags of the open hearth process, and the total volume of slag is much less than in the straight open hearth process, so that the loss of iron here is perhaps less than in the latter process. The chief loss is at the converters, and there can be no doubt but that the double conversion loss exceeds the single loss in the straight open hearth process. This matter assumes its chief importance as it relates to the conservation of the iron ore supply.

SECTION III.

COMBINATION PROCESSES FOR HIGH PHOSPHORUS IRON.

The Duplex Process in the South: In the southern district, the conditions of steel manufacturing are very different from those in the North, and many additional reasons for the use of the duplex process there are to be found. First, in the South there is no pig iron that is suitable for the Bessemer process manufactured there, whereas, in the North, Bessemer iron is relatively abundant. Second, there is no low phosphorus iron or spiegel commercially available for recarburizing in the southern district as there is in the North, and this lack makes it necessary in manufacturing high carbon steels in the South to catch the carbon on the way down. Third, the phosphorus content of the basic iron in the southern district, which averages about .80 per cent., is very high as compared with the phosphorus content of basic iron in the North, the average for which is about .25 per cent. In the manufacture of high carbon steel from high phosphorus pig iron, the duplex process offers exceptional advantages for catching the carbon high, thus reducing the amount of coal or coke-dust required to a minimum and avoiding rephosphorization from the high phosphorus slag. Another advantage of the process, when iron with a

high phosphorus content is used, is that it permits the making of a slag which contains a high percentage of phosphoric acid and is therefore suitable for use in the manufacture of fertilizers. This slag is a valuable by-product from one of the southern plants.

Triplexing Processes: In operating the duplex process on very high (over .8 per cent.) phosphorus pig iron it has been found that, owing to the high phosphoric acid content of the slag, it is difficult to prevent the reduction of some of the phosphoric oxide after recarburizing. This re-phosphorization of the steel occurs mainly in the steel ladle and affects the composition of that portion of the metal in direct contact with the mass of floating slag. This action, therefore, is liable to cause a noticeable increase in the phosphorus content of the last two or three ingots cast from each ladle of steel. This defect can be overcome only by changing the slags near the end of the heat, and finishing the steel under new slag low in phosphorus. This change of slags can be made in the same furnace in which the metal is purified. But, as this practice delays the heat somewhat, it is sometimes advantageous to employ a Triplex Process in which the purified molten metal is tapped from the purifying furnace and transferred to a second basic furnace where the metal is finished under a low phosphorus slag. Then, when this metal is tapped from the finishing furnace, there will be little danger of reducing the phosphorus compounds of the slag that covers the metal in the ladle. For large tonnages of steel of ordinary quality a tilting basic open hearth furnace will be used for finishing, but for steel of extra-fine quality the basic electric furnace will be employed.

PART II.

THE SHAPING OF STEEL.

CHAPTER I.

THE MECHANICAL PROPERTIES OF STEEL.

SECTION I.

SOME GENERAL REMARKS PERTAINING TO THE TESTING OF STEEL.

The Factors that Affect the Mechanical Properties of Steel: Of all the properties exhibited by steel the mechanical properties are, perhaps, the most important, because these are the properties that describe the behavior of the metal under stress, and are also the properties that may be varied to the greatest extent. Four factors are chiefly operative in varying and regulating these properties; namely, the method of refining the metal, its chemical composition, the mechanical working it is subjected to, and the heat treatment it receives. The first of these factors is discussed in the first part of this book. The others are now to be taken up, and frequent use of the terms employed in the mechanical testing of steel will be made in the pages to follow. Hence, although in the natural order of manufacturing steel, physical tests follow the shaping, it seems well to take up this subject now in order that the reader may be more familiar with the terms employed in connection with these tests, when there is occasion to refer to them.

The Two Objects in the Testing of Steel: In the early days it was the custom to order steel according to use, that is, the purchaser asked the steel maker for a certain quantity of steel suitable for a certain purpose, and the manufacturer then furnished steel of a kind or grade he considered most suitable for the purpose. With the growth of the steel business, this custom proved inadequate to the conditions and was superseded by the practice of ordering steel to specifications, which appeared to be, and is, a much more satisfactory arrangement for all parties concerned. The consumers came to the decision that they should know better than anyone else what the requirements were, and the manufacturer, in turn, was very glad to be relieved of the responsibility he assumed under the old system. Now, the only basis upon which the consumer of steel or his engineers originally had to work in determining specifications was experience. Thus, providing that a certain steel had proved satisfactory for a certain purpose, he desired for the new work steel as nearly like the old as possible. With

this progress came the need for testing. Then, as undertakings involving the use of steel increased in magnitude, it was discovered that steels made by the same methods are subject to considerable variation. Furthermore, in order to obtain the requisite amount of steel, it is often necessary to use, for the same purpose, steels made in different ways. And again the need for testing was felt in order to secure uniformity in the materials. This testing developed along two lines, namely, physical and chemical.

Relative Importance of Physical and Chemical Testing: It is evident that, to the consumer of steel, its mechanical properties are of first importance, because it is these properties that determine whether or not a particular steel is suitable for the purpose he intends it. In all cases, then, such as structural steels, in which the material is put in service as received from the manufacturer, the customer does well to order his steel to physical specifications only. In cases where the steel is to be heat treated or is to undergo other treatment in the hands of the customer, then it should be ordered to a chemical specification only. Since the method of manufacture influences the properties of the metal, the kind of steel, whether Bessemer, basic, acid, or electric, should be and is, usually, specified. But for a great many reasons, for a discussion of which time and space are not available, it is unfair to ask the manufacturer to make steel to order in which all three factors are specified. Suffice it to say, that in the one case the customer should be satisfied to get the kind of steel ordered with the required physical properties, irrespective of the means, chemical or otherwise, which the manufacturer may have found it necessary to employ in order to supply metal with the properties called for. In the other case, the purchaser is interested only in obtaining steel properly made and of the proper kind and composition, because with such steel the original physical properties will be replaced by new ones due to the subsequent working or treatments. From the view point of the consumer, then, the relative importance of the physical and the chemical test depends upon the conditions that surround each individual case. But to the manufacturer, chemical testing is of prime importance, because it offers a means of control whereby he is able to produce the steel with a greater degree of certainty. For a description of the methods employed in chemical testing, the published standard methods of the chemists of the United States Steel Corporation are available.

Nature of Physical Testing: It should at all times be borne in mind that the results obtained by any method of physical testing are not absolute, but relative. Obviously, the only sure test is actual service, and it is just as evident that such tests are impracticable. Therefore, the test must be carried out with a small piece of material, the structure and condition of which are likely to be different from that of the section, taken as a whole, from which it was cut. A second objectionable feature is found in the difficulty of subjecting this piece to the same conditions that it would be subjected to in actual service. Attempts have been made to

analyze these conditions with the idea of classifying the forces steel is required to overcome in service, so that, in testing, it might be subjected to the same kinds of forces. With respect to the direction in which they are applied, forces have been classified as (1) tensional, or forces tending to put the material under tension, that is, pull it asunder; (2) compressional, or forces that tend to compress the piece in one or more directions; (3) torsional, or forces tending to twist the material; and (4) shearing, or forces that tend to cut the material across its section. With respect to the manner in which the forces are applied, the following classification has been made: 1. Static stresses, which are the result of the gradual application of a steady or constant load. 2. Fatigue stresses, such as result from the repeated application of a load or loads. 3. Impact stresses, in which the metal is subjected to a sudden blow. 4. Dynamic stresses, which are repeated impact, or vibratory stresses.

From these are selected the class of force or stress the steel is likely to be required to withstand in service, and the tests will be arranged accordingly. Added to these are a number of miscellaneous tests, such as hardness tests and tests to determine relative resistance to wear or penetration.

SECTION II.

THE TESTING OF STRUCTURAL AND OTHER SOFT STEELS.

The Pulling Test: A test that is most commonly applied to steel, and one that is always used, almost to the exclusion of all others, for testing structural steels, is that commonly spoken of as the pulling test. As the name implies, the chief aim in this test is the determination of the tensile strength of the steel, but incidental to the carrying out of the test much additional information as to other mechanical properties of the sample of steel is obtained. The technical terms employed in testing to indicate these properties are tensile strength, elastic limit, elongation, reduction of area, and modulus of elasticity. The exact meaning of these terms is best explained in connection with a description of the method of making the test.

Procuring the Test Pieces: Except in one or two cases where it is desirable to modify the usual procedure, the test piece, or sample, is sheared from scrap ends cut from the material as it comes from the rolls. This piece is about eighteen inches in length and two inches in width, and, except in the case of sheared plates from which both longitudinal and transverse pieces are sometimes taken, its long axis is parallel to the direction of rolling. As a rule, the test piece is taken from a position not too close to the rolled edge, but in the case of bars of small sectional area the entire section of the proper length may be taken. The piece is then stamped near the ends with the heat number and any other data necessary to identify it.

Preparation of the Test Piece: The working or shearing of the test piece puts it in a state of strain and produces a great number of incipient cracks on the edges, so that if it were pulled in this condition it would fail too easily, and the results of the pulling would not indicate the real value of the properties determined. To eliminate these cracks, the edges of the piece are milled off as shown in the accompanying sketch, and the milled

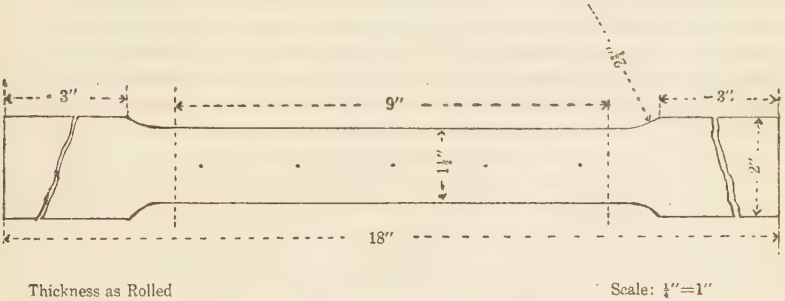


FIG. 109. Diagram Showing the Usual Form of the Test Piece Used in Pulling Structural Steels. Occasionally the edges are milled parallel for the full length of the specimen.

edges are filed smooth. Then if the piece is a heavy, thick one, or is an alloy steel, such as nickel steel, it is allowed to rest for a period, the length of which will depend upon the conditions and the kind of steel. This resting is necessary to allow the steel to relieve itself of the condition of strain which the working has set up in it. This condition seriously affects the ductility of the steel, as is shown by the fact that some test pieces, particularly of alloy steels, show a marked improvement in elongation after resting, but with little, if any, change in the tensile strength. In the case of soft steels of moderate thickness, the resting period is not so important, as the working does not produce severe strains, and such steels recover quickly from strains. After the test piece has been machined and filed and otherwise made ready for testing, its dimensions are taken. From a point estimated to be the middle of the machined portion of the piece, two spaces of two inches each are laid off, with a double pointed punch, longitudinally along the bar and in both directions from the center punch mark, thus making a distance of eight inches between the two punch marks that are the farther from the center one. This space fixes the length of bar that is later to be the basis for calculating the percentage of elongation. Finally, with screw micrometers the width and thickness of the test piece are taken and recorded. A careful operator will measure these dimensions in three or four places to determine to what extent they are uniform. The test piece is then ready to be pulled.

Pulling the Test: The testing machine may be likened to a beam scale or weighing machine, and if, instead of lying upon the platform of the scale, the test piece be thought of as being attached by one of its ends under the platform with its other end free for the attachment of some device for exerting a vertical pull, the analogy is almost exact. In modern machines the pulling device is either an electric motor, attached through gears and screws to a gripping device that clamps one end of the test piece, or an hydraulic ram connected directly with the clamping device. With such an arrangement the amount of the pull is registered in pounds on the graduated beam of the machine. This beam is provided with a travelling weight, which, by means of a screw and worm drive actuated by hand, may be rolled out along the beam as the pull increases, thus keeping the beam in the neutral position and registering the amount of the tension at all stages of the pull. When the test has been properly marked and measured, it is placed in the machine in a vertical position and securely clamped in the gripping boxes, or shackles. Then, the pulling device is started at low speed, and the weight is cautiously moved out along the beam, the operator keeping it in a perfectly horizontal position with the free end midway between the upper and lower beam-end stops. The continued action of the pulling machine is an indication that the test piece is stretching slightly. That such is actually the case could be proved by stopping the machine and measuring with delicate instruments the distance between the two extreme space marks and comparing this measurement with the original length. As the pulling is continued uniformly, the beam weight is advanced at a uniform rate, indicating that the piece is obeying the law of stress and strain; but a point is soon reached where the beam suddenly drops, indicating that, without any increase in the load, there has been a sudden increase in the length of the test piece. In testing parlance this point is called the **proportional limit,** the **elastic limit,** the **yield point,** or the **point of permanent set.** Though defined in different terms, the proportional limit and the elastic limit are practically the same; likewise, the yield point and point of permanent set are identical. For the sake of accuracy, only the last two terms should be applied to the point in question, because, owing to the lack of sensitiveness of the machine and the speed at which it is operated in actual practice, the beam will not drop until after the true elastic limit stress has been passed. However, the reading at the drop of the beam, if carefully made by an experienced operator, is near enough the true elastic limit for all practical purposes. A reading of the weight indicated by this position of the beam weight is therefore taken, and the pulling is continued as before, with the exception that the speed of the pull may be increased somewhat. In a short time another point is reached where the beam suddenly drops for the second time, but here, though the pulling is continued, the beam will not rise again. A second reading is therefore made, and the weight recorded is taken as a measurement of the **tensile strength** of the test piece. Finally, as the machine continues to elongate the specimen, the point of

rupture is reached, and the piece breaks apart. In practice no reading is taken at the breaking point, but if it were, it would be necessary to reverse the direction of motion of the beam weight, because the **breaking load** is generally less than the tensile strength. The latter, therefore, is usually referred to as the **ultimate strength, maximum stress,** or **maximum load.**

Graphic Representation of Tests: The pulling of a test is admirably illustrated by means of a graph, which is also a great aid in understanding the relations of the various terms employed in designating the points described above. The following graph, while not absolutely accurate and to scale in some of its parts, will serve to illustrate the scheme for preparing graphs and to make clearer the description of the pulling of the test piece. The diagram requires no explanation.

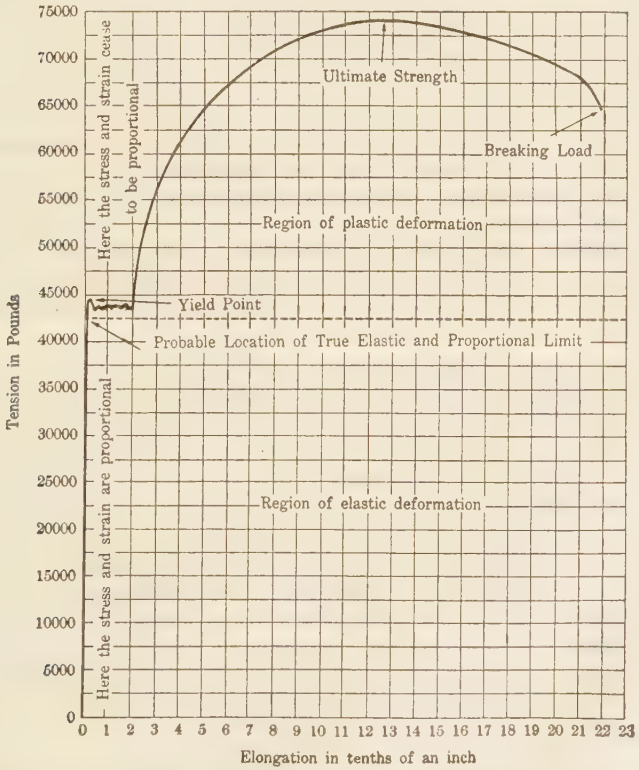


Fig. 110. Graph Representing the Pulling of a Structural Steel Test Piece.

A Theory to Explain the Elasticity of Steel: While the elastic limit is characteristic of all elastic bodies, the yield point can be easily detected in only a few metals, and is most pronounced in pure iron or low carbon plain steels. As to the relation between the maximum stress and the breaking load, this varies according to the ductility or hardness of the metal. In untreated high carbon steels, for example, the maximum load and the breaking load are almost the same. The most plausible theory to account for these points is based on the minute structure of the material. That bodies of iron and steel consist of grains, or imperfect crystals, is evident from the photomicrographs of Fig. 70, page 238, and Figs. 112 to 115, pages 428-9. That these grains, or crystals, are themselves made up of small bodies and result from a tendency of the molecules—or, since iron molecules are monatomic, the atoms—to assume a definite arrangement in passing from the liquid to the solid state, had long been suspected, but up to 1915 no method of proving this supposition had been discovered. In 1917, Hull[1] published a paper entitled, "A New Method of X-Ray Crystal Analysis," and since that time several investigators, by means of the X-ray, have shown that, in the case of iron or steel normally cooled, the structure of the grains simulates that of a body made up of most closely packed cubes with one atom located at each corner, and one at the center of each cube. This regular arrangement of the atoms follows a definite pattern, known as the **body-centered cubic space lattice,** and exists throughout each grain, except at the grain boundaries, where the atoms have a haphazard arrangement, forming a thin film, known as vitrious or amorphous cement,[2] which serves to cement the different grains together. While at high temperatures, or under some conditions of loading, this amorphous metal may be weaker than the crystalline, under normal conditions, atmospheric temperatures and static loading, it is stronger.

The Property of Elasticity, however, cannot depend solely upon the position of the atoms, but upon the interatomic forces. From a study of cohesion and the phenomena produced by temperature changes, the atomic forces may be imagined as being of two kinds. The atoms of the metal have a certain attraction for each other, which varies inversely as, say, the square of the distance between them; and each atom is in a state of constant vibration, the force of which depends upon the absolute temperature. In the fluid states, the amplitude of these vibrations is so great that the atoms are unable to assume any fixed arrangement with respect to each other. In the solid state, the force producing the vibrations is less than in the fluid states, and the amplitude is so small that the atoms are drawn into groups by the attractive forces, as the metal passes from the liquid to the solid state. The atoms, however, are still prevented

[1]See Physical Review, Vol. 10, No. 6, December, 1917.

[2]The Amorphous Metal Theory was first advanced by George T. Beilby in a paper entitled, "The Hard and Soft States in Metals", published in 1911. See J. Inst. Metals.

from coming into contact with each other by the amplitude of their vibrations, which acts as a repelling force, since the force of vibration is still greater than the force of attraction. Hence, the atoms in each group are drawn into positions that will establish equilibrium among all these forces. The distance between the nuclei of any two atoms must be twice or more than twice the amplitude, and is known to be several times the diameters of the atoms themselves, hence a slight displacement of the atoms should be possible without breaking any of the atomic bonds. Now, any external force applied to a single crystal will at first tend to displace the atoms and disturb the equilibrium of forces, but so long as the displacement does not exceed a certain maximum amount, which is defined as sufficient to break the atomic bonds, the atoms will resume their original positions upon the removal of the stress, causing a body made up of such crystals to display the property of elasticity. This maximum stress corresponds to the elastic limit, and the slight change in form brought about by a stress under the elastic limit is known as **elastic deformation.** In the pulling test just described, the force of the pull is transmitted to each crystal or grain along lines parallel to the direction of the pull, because the amorphous cement films, being stronger than the crystals themselves, maintain the cohesion among the crystals unimpaired.

Reasons for the Yield Point: If, in the case of any grain, the force of the pull is increased to the point where the displacement of any, or all, of the atoms exceeds the strain at the elastic limit, they will not return to their original positions on release of the stress, and the crystal remains permanently deformed. In the case of iron, as well as other ductile metals, this statement does not mean that all the atoms are simultaneously displaced to the same degree when deformation occurs; for it has been shown by Rosenhain[1] and, later, by many others that the deformation results from a kind of block movement or slip along certain planes passing through the crystal. These facts fit in very nicely with the conception of a cubical, block-like structure of the grain obtained from X-ray examinations, for in such a regular arrangement of the atoms it is evident there are planes which contain a fewer number of atoms per unit area than others, and that this difference in atomic concentration gives rise to planes of weakness. In ductile metals the displaced atoms are able to form new bonds with other atoms and thus retain their cohesion, but in brittle substances the atoms or molecules possess this power only to a very slight degree. Hence, any marked displacement, or breaking of atomic bonds, in the latter substances results in complete rupture. In the case of ductile metals, therefore, the planes of weakness are called **slip planes** to distinguish them from **cleavage planes,** which are applied to the corresponding planes of brittle crystals. Now, the reason for the yield point is evident, for it is plain that the force required to start the slip must be greater than that necessary to continue the movement. In the case of commercially pure iron and soft

[1]See "An Introduction to the Study of Physical Metallurgy, by Walter Rosenhain; D. Van Nostrand Co., New York, N. Y.

steels there is nothing to offer much resistance to the slip, which, therefore, occurs on a great many planes in many different crystals at once, hence the beam of the testing machine drops.

Reasons for the Maximum Stress: As soon as the elastic limit is passed, complete rupture of the body is inevitable, unless some forces are brought into play to stop this slippage. Two theories have been advanced to account for the stoppage of slip. According to Beilby's amorphous metal hypothesis, the slip was supposed to bring about a disorganization of the atoms adjacent to the slip plane, forming a layer of amorphous metal similar to that at the grain boundries, and strong enough to stop the slip. With this theory, Jeffries and Archer[1] disagree, holding that "In a metal composed of an aggregate of grains the slip is stopped partly by the interference of adjacent grains and partly by resistance on the slip plane itself." The resistance generated on the slip plane may be due to a slight disorganization of the atoms, which results in greater cohesion, or to a condition in which, as they glide past each other, they reestablish new bonds with other atoms. The interference to slip offered by adjacent grains is easier to visualize. In a body made up of a number of grains, the orientation, or direction of the slip planes, is different in each grain, or, at least, in nearly every grain. Slip will start first in those grains in which the slip planes are parallel, or nearly parallel, to the direction of the impressed force. The adjacent grains will then tend to stop this slip, because, since their slip planes lie at different angles, the force producing the slip in the original crystals will be resolved into two or more forces acting at angles to the direction of slip in the adjacent plane. Consequently, the strength of the material, or the force required to produce further slip increases, and continues to increase, until all the grains are slipping, or undergoing deformation, on many different planes. Before this condition is reached in pulling a test piece, however, it is likely that some grain or grains among those first to slip become elongated to such an extent that rupture occurs in it. Such an event throws more stress upon adjacent grains, and the piece as a whole begins to "neck" down at that point. This process will continue at the point of weakness, until the piece as a whole is ruptured. During the pull all the grains thus become elongated, mainly in the general direction of the pull, and, since the volume of metal remains practically constant, the piece as a whole stretches or elongates only by becoming smaller in cross section. This permanent deformation in crystalline bodies is known as **plastic deformation,** which term is used to distinguish this phenomenon from the flowing movement exhibited by amorphorus bodies under stress, which is called **fluid deformation.** With this understanding of the subject it is clear that the maximum stress does not represent the total force of attraction between the atoms, also that the breaking load is less than the maximum stress because of the necking down of the piece, and because rupture of the piece takes place progressively.

[1]See "Science of Metals," page 80, by Zay Jeffries and R. S. Archer, published by McGraw-Hill Book Co., New York, N. Y.

Examination of Test After Pulling: After fracture, the two parts of the test piece are removed from the machine, and the fractured ends are fitted together as neatly as possible for the measurements to follow. The distance between the extreme punch marks is now measured. The difference between this distance and the original space of eight inches gives the elongation for the piece, which is properly recorded. An examination of the piece shows that while it has been reduced in section throughout its length, the reduction is most pronounced in the region of the fracture, where the piece underwent the characteristic deformation known as **necking** before it broke. It is here, as near to the fractured ends as possible, that the width and thickness are again measured in order to ascertain the reduction in area. Finally, the fractures are designated as angular, cup-shaped, half cup, and irregular. Very little importance can be attached to the form of the fracture, but some inspectors believe that the cup-shaped fracture indicates more nearly perfect uniformity in the material than the other forms.

Calculating the Results of the Test: The results obtained in the test are for the given piece only, and, in order that the results from different tests may be comparable, they must be calculated to a common basis. Tensile strength and elastic limit are always expressed in pounds per square inch in the United States, in gross tons per square inch in England, and kilograms per square millemeter in France and other countries using the metric system. The elongation is expressed as the percentage of increase on the original length of the bar. In the United States this length for structural and other low carbon steels is usually eight inches, as formerly stated, but other lengths, as ten and twelve inches, ten centimeter, etc., may be used. For this reason it is always important that the original length of the bar be stated, as the percentage of reduction on two inches, for example, would be much greater than that based on eight inches, because of the pronounced local contraction, or necking, at the point of fracture. This variation in the length of test pieces is made because the relation between the length and the thickness of the test affects the elongation. Hence, in order that tests of different thicknesses may be comparable, the ratio between the thickness and length is kept constant by varying the length. The ideal thickness for a length of eight inches is about three-fourths inch. Over or under this thickness, the specification is usually modified either by changing the length or by making the proper allowance from the elongation as determined. The reduction of area is expressed in percentage contraction of area of the cross section as compared with the original area of the cross section. An example will serve to clear up any doubtful points that may not have been made clear in this explanation.

Table 55. Data on the Pulling Test Represented by the Graph of Fig. 110.

	Dimensions of Piece	
	Before Pulling	After Pulling
Length	8.0 inches	10.20 inches
Width	1.41 "	1.00 "
Thickness	.860 "	.60 "
Area	1.213 sq. in.	.60 sq. in.

Readings on pulling bar: Elastic limit=44600 lbs.; Ultimate strength=74600 lbs.

Calculations:

$$\text{Elastic Limit} = \frac{44{,}600}{1.213} = 36770\text{-lbs. per sq. in.}$$

$$\text{Ultimate Strength} = \frac{74{,}600}{1.213} = 61500\text{-} \text{ " " "}$$

$$\text{Elongation} = \frac{10.20-8}{8} = 27.5\% \text{ in 8 inches}$$

$$\text{Reduction of Area} = \frac{1.213-.60}{1.213} = 50.5\%$$

The Modulus of Elasticity, or Young's Modulus: The Modulus is seldom determined in practical work, as it involves the determination of the absolute increase in length of the test bar up to the elastic limit, which is a quantity so small as to be very difficult to determine accurately. It may be defined as that force, expressed in pounds, tons, or kilograms per unit of cross section area, that would stretch a test piece to twice its original length, when applied to one end of it and acting in the direction of its length. It may be found by applying the following formula: $M=\frac{f \times L}{A \times l}$ where M= modulus of elasticity, f=force applied, L=original length, A=original sectional area, l=increase in length. For low carbon steel Young's Modulus is about 29,000,000 lbs.

Relative Importance of the Mechanical Properties as Determined by the Pulling Test: From what has been said it is plain that the quantities that may be taken as indicative of the strength of the material are tensile strength and elastic limit; but while most engineers will insist on both tensile strength and elastic limit being given and a few are content to get the tensile strength only, it is evident that, in its practical application, the elastic limit will determine the working strength of the steel, that is,

the maximum load a given piece may carry with safety. In the elastic range the body stretches and recovers with increase and decrease in the load; in the plastic range it cannot recover but continues to elongate as long as tensional stresses are applied, and in this condition it is a very unsafe material to use. The percentage reduction of area and the percentage of elongation are, when considered together, an index of the ductility of the metal, for both are required to give an idea of the amount of the deformation before rupture. However, engineers are divided in their opinions as to the relative importance of the two factors. In a general way, it may be stated that the reduction of area is regarded as more reliable than elongation, because, as previously explained, the quantity denoting the latter is affected by the ratio of the length of the test piece to its cross sectional area. In many foreign countries this ratio is always specified.

Bending Tests: On certain classes of material, bending tests are made in addition to the pulling test. These tests, simple in character, consist merely in bending test pieces similar to those used for pulling, and similarly prepared, through certain specified arcs. The bending is usually on cold material, but some orders call for hot bending tests, also. Such tests are employed to make sure that the steel is not cold short or hot short and, in a way, to indicate the ductility of the metal.

SECTION III.

THE TESTING OF THE HIGHER CARBON AND HEAT TREATED STEELS.

Kinds of Tests Applied to the Higher Carbon and Heat-treated Steels: For testing the class of material referred to under this heading, a large number of different tests have been devised. These tests may be classified under the headings of tensile tests, compressive tests, torsional tests, impact tests, and hardness tests. Of these, the tensile, impact, and hardness tests are the ones most frequently met with, and will, therefore, be described later. Of the others the torsional test is perhaps the most important, as it is largely used in the testing of steel for automobiles. It consists in twisting a small round specimen of steel held in a suitable machine until rupture occurs. In it a test piece of standard size is used, and values for this piece corresponding to the elastic limit and ultimate strength, but expressed in inch-pounds, are obtained very much as in the tension test; the amount of distortion, however, is given in degrees. The compression test is carried out by means of a machine similar in construction to the pulling machine. The test piece may be in the form of a small cylinder or a one inch cube. The elastic limit under compression is determined, and the distortion is indicated by the decrease in length.

The Tensile Test: The test for determining the tensile strength of the higher carbon and heat treated steels is carried out in a manner similar to that for the softer steels, but since the material is so much stronger, and the items made from such steels do not lend themselves to the same method

of sampling, the test piece is much smaller than that employed in the case of structural steels. This specimen is in the form of a small round, as shown in the accompanying figure, and is often obtained by boring with a hollow drill about midway between the center and outside surface of the section sampled.

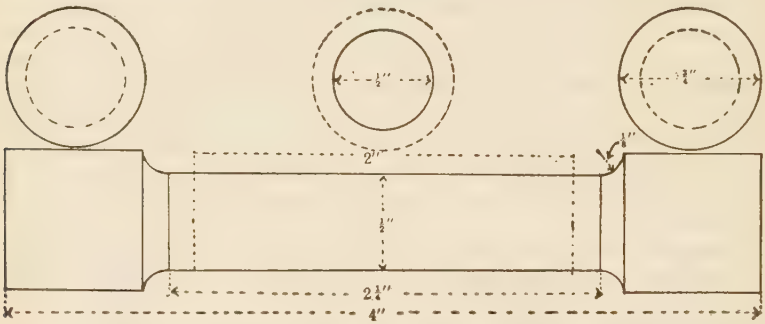


FIG. 111. Drawing Showing Usual Size and Form of Test Piece Used in Pulling High Tensile Steels. The ends may be of any form desired but the central machined portion must be as shown in the figure.

Impact Test: While several different types of machines for measuring the resistance of steel to impact have been invented, the results obtained with any of these machines so far have not been considered very reliable, as widely varying results may be obtained on the same steel tested on the same machine. In practice, therefore, the nearest approach to an impact test is what is commonly and correctly called the **drop test.** It is applied to full size pieces of rails, to axles, and to other sections. It consists in allowing a specified weight to drop from a specified height a specified number of times upon the sample, which is supported at two points on a heavy anvil or block resting upon strong springs. All three of these factors may vary greatly with different classes of material and with the different ideas of the engineers. While it does not measure absolutely any property of the metal and is to be considered as comparative or qualitative only, it is, nevertheless, one of the most useful of practical tests, for it determines, in a crude way, the ductility and homogeneity of the metal and its resistance to shock. In the case of axles and other round bodies, the deflection from a given weight may be kept constant for different sizes by varying the height, for since the strength of such a section varies as the cube of the diameter, for equal deflections, the height varies as the cube of the diameter of the specimen at its center.

Hardness Tests: The best known and the most widely used instruments for measuring the hardness of metals are the Shore scleroscope and the Brinell ball testing machine. The Shore instrument consists of a small diamond-faced tup enclosed in a glass tube which is provided with a suction bulb, whereby the tup may be raised to the top of the tube and dropped from

a definite and fixed height. To make a determination, the instrument is held in the vertical position with the lower end resting upon a smooth and highly polished spot on the surface of the metal to be tested, when the tup is allowed to drop by compressing the bulb. The height of the rebound, which may be read on a scale inscribed on the tube, is taken as a measurement of the hardness. Notwithstanding the fact that the results obtained by this instrument are sometimes very erratic, especially if the surface of the different spots tested have not been properly and uniformly polished, it is a valuable instrument for comparing the surface hardness of different parts of a body that is too large to be tested in any other way. It also possesses the advantage that the tests may be made upon the finished article without injury to the article itself.

Brinell Hardness: The Brinell hardness test measures the ability of the metal to resist penetration by a small ball when propelled by a gradually applied force. It consists in pressing a hardened steel ball into the surface of the specimen under test by means of a fixed load gradually applied. The instrument consists essentially of a small hydraulic press, which is operated by a small hand pump and is provided with a pressure gauge for reading the pressure, and a special contrivance for automatically holding the pressure when it has reached a maximum of 3000 kilograms. The piston of the press, which acts vertically downward, is provided on its end with a hardened steel ball, ten millimeters in diameter, by means of which an impression may be made on the smooth surface of the specimen, which rests on a firm but an adjustable base. The operation of the instrument is very simple. The specimen, the surface of which has been planished with a file, a whetstone, emery wheel or similar means, is laid on the base and is then brought in contact with the ball by turning a small wheel for adjusting the base, or platform. By operating the hand pump until the maximum pressure is attained and maintained for about one half minute, the steel ball is pressed into the surface; then the pressure is relieved, the base is lowered, and the diameter of the impression made in the specimen is measured by means of a microscope fitted with a millimeter scale, vernier, and cross hair. From this diameter the spherical area of the impression may be calculated, which, divided into the maximum load of 3000 kilograms, gives the hardness number. The formulas for making these calculations may be combined into a single formula, thus:

$$H=\frac{P}{2\pi r\left(r-\sqrt{r^2-\frac{D^2}{4}}\right)}$$

where P=3000 Kilograms pressure, r=5 mm., radius of the ball, D=diameter of the impression, and H=the hardness number. In practice it is most convenient to have a table, such as that shown on the next page, prepared, from which the number may be obtained direct from the diameter of the impression.

Relation of Brinell Number to Tensile Strength: It is both a curious and a significant fact that the Brinell hardness number bears a close relation to the ultimate strength, as may be seen from an inspection of the following table, which was prepared only after comparing results obtained upon thousands of specimens, to which both the Brinell and the pulling tests had been applied. This relation, it will be observed, is approximately 500, and holds for all grades of carbon steel whether they be heat treated or in their natural state as forged or rolled. For this reason the Brinell test is applicable to the rapid testing of steel from which samples for the tensile test cannot be obtained.

Table 56. Brinell Hardness Numbers and Estimated Tensile Strength for 3000 Kilogram Pressure on a 10 MM. Ball Testing Machine.

Diam. of Impression in m/m	Hardness Number	Ultimate Pounds per Sq. In.	Diam. of Impression in m/m	Hardness Number	Ultimate Pounds per Sq. In.	Diam. of Impression in m/m	Hardness Number	Ultimate Pounds per Sq. In.
2.00	946	465100	3.35	332	162700	4.70	163	80100
2.05	878	442100	3.40	321	157800	4.75	159	78300
2.10	857	421600	3.45	311	153100	4.80	156	76600
2.15	817	402000	3.50	302	148600	4.85	153	74900
2.20	782	383700	3.55	293	144300	4.90	149	73300
2.25	744	366600	3.60	286	140200	4.95	146	71700
2.30	713	350600	3.65	277	136200	5.00	143	70200
2.35	683	335700	3.70	269	132400	5.05	140	68700
2.40	652	321600	3.75	262	128800	5.10	137	67200
2.45	627	308400	3.80	255	125300	5.15	134	65800
2.50	600	295900	3.85	248	121900	5.20	131	64500
2.55	578	284300	3.90	241	118700	5.25	128	63100
2.60	555	273300	3.95	235	115500	5.30	126	61800
2.65	532	262900	4.00	228	112600	5.35	124	60600
2.70	512	253100	4.05	223	109700	5.40	121	59400
2.75	495	243800	4.10	217	106900	5.45	118	58200
2.80	477	235000	4.15	212	104200	5.50	116	57000
2.85	460	226600	4.20	207	101600	5.55	114	55900
2.90	444	218700	4.25	202	99100	5.60	112	54800
2.95	430	211200	4.30	196	96700	5.65	109	53700
3.00	418	204100	4.35	192	94400	5.70	107	52700
3.05	402	197300	4.40	187	92200	5.75	105	51700
3.10	387	190800	4.45	183	90000	5.80	103	50700
3.15	375	184600	4.50	179	87900	5.85	101	49700
3.20	364	178800	4.55	174	85800	5.90	99	48800
3.25	351	173200	4.60	170	83900	5.95	97	47900
3.30	340	167800	4.65	166	82000			

$\frac{\text{Pressure}}{\text{Area of Impression}}$ = Hardness Number.

Tensile in Kg. per Sq. MM. = Coefficient .346 x Hardness Number.

Factor to Convert Kg. per Sq. M/M to Lbs. per Sq. In. = 1422.3

CHAPTER II.

THE MECHANICAL TREATMENT OF STEEL.

SECTION I.

METHODS AND EFFECTS OF MECHANICALLY WORKING STEEL.

Methods of Shaping Steel: After the separation of the metal from its ores, which in modern practice is accomplished by means of either the blast furnace or a form of electric furnace, and its purification in the Bessemer converter, open hearth, puddling furnace, or electric furnace, the third step in the metallurgy of iron is the reduction of the large bodies of metal thus produced to the various forms and sizes required by the many uses to which it is to be put. In general this shaping may be brought about either by pouring the metal while in a molten state into moulds, which act is called casting, or by mechanically working it. Since by all the methods of purification, puddling excepted, the metal is obtained in the fluid state, casting would appear to be the simplest and cheapest method of shaping; but for forming articles of very small section, it is evident that this method is impracticable; nor is it used, unless unavoidable, to form the larger sections in which the mechanical properties of the metal must be devoloped to the highest degree. Some shapes on account of their size or their intricate design require casting, while others are cast because they require no great strength in service and the cost of production only is to be considered. A lack of strength and ductility in castings is inherent, and is due to chemical and physical phenomena that accompany the solidification of the molten metal, something about the nature of which will be explained later in connection with the cooling of ingots. Suffice it to say now that the weakness of castings is due chiefly to any or all of three causes, namely, blow holes, segregation, and the formation of large crystals.

Benefits of Mechanical Working: On the other hand, mechanical shaping improves the quality of the metal by forcing its particles into more intimate contact, closing up cavities, and by refining its crystalline structure, and so has important functions aside from the mere reduction to form and size. The change in properties that may be attributed to the process of mechanical working is a marked one, for the strength, ductility and hardness are all affected. Of these properties the strength is always increased by the working, the hardness may or may not be markedly increased, while the ductility, i. e., elongation and reduction in area, may be either increased or decreased, depending on the conditions of the working. The amount of change in each of these properties for a given steel of a certain chemical composition is affected by the amount of work done and by the temperature at which the working is carried on.

The Two Temperature Ranges of Working: In considering the mechanical treatment of steel, or of any metal, the first distinction to be made is that of hot and cold working. These terms, hot and cold, as they are commonly used, are indefinite, or relative, only, but as applied to the mechanical working of steel, they are separated by a sharp and well-defined line, in the case of any particular class of steel, at least. This line is described by the temperature at which rapid crystalline, or grain, growth occurs, and rapid grain growth, being a physical phenomenon similar to fusion or boiling, begins at a definite temperature for any single substance, if other conditions are constant. Since grain deformation and grain growth form the basis upon which the division is made, a study of metallography is necessary to a thorough understanding of this subject. But the study of the metallography of steel is too large a subject to be treated of here. Therefore, the following brief discussion is intended merely to serve as an introduction to the subject and as a means that will, at least, lead the student to a better appreciation of the effects of working the metal in these two temperature ranges.

Cold Working: To begin this study, let it be assumed that a certain piece of soft or medium carbon steel is to be worked at ordinary room, or atmospheric, temperatures. If this steel has been previously subjected to hot working, as ordinarily would be the case, it will exhibit certain mechanical properties, and will have a structure like that shown in the photomicrographs of Fig. 113 or Fig. 115, or, since these figures represent extremes as to grain size, its structure may be an intermediate between these two. These photomicrographs show that the metal is made up of two constituents, the white areas representing grains of pure iron, or ferrite, and the dark areas, grains of pearlite, which is composed of pure iron and iron carbide in definite proportions. If now the piece of steel is mechanically worked, i. e., hammered, rolled, drawn, or otherwise permanently deformed, its mechanical properties are changed, and its structure becomes like that shown in Fig. 114. This structure is similar to that shown in Fig. 115 except that the grains have been somewhat elongated. If the piece is tested immediately after the deformation takes place, it will have no elastic limit, but the tensile strength and hardness will now be much higher than before the steel was worked, while the ductility, as represented by the elongation and reduction of area, will be decreased. The manner in which the grains become deformed and the reasons for the increase in strength and hardness, both of which but represent the resistance of the metal to deformation, have been fully explained in connection with the pulling test, which is but a particular case of cold working at the same temperature. If, instead of testing the piece at once, it is allowed to rest for a period of several weeks at room temperature or for a day or so at a higher temperature of, say, 100 to 150° C., it will regain some of its elasticity, but the elastic limit will be much higher than before it was worked. This phenomenon can be explained by assuming that the disorganized atoms, by virtue of their vibratory motion,

are able to rearrange themselves to some extent even at ordinary temperatures. This ability, of course, would be increased by increasing the energy of the vibrations, that is, by increasing the temperature of the piece. Up to 300° C. (572° F.), however, the microscope reveals no change in the structure, but between 300° C. and 520° C. (968° F.), a gradual change in the strained grains can be observed. Above 520° C., the change in structure takes place more rapidly, until at 600° C. (1112° F.), what appears to be new grains form in a very short time, and the mechanical properties, if the steel is of low carbon content, approach the values they had in the beginning, so the steel is said to be annealed. This statement does not apply to high carbon steel, because the change affects only the ferrite grains, the pearlite grains retaining their elongated form. These new ferrite grains have almost the same form as the original grains, but are at first smaller. If the steel is held at the annealing temperature for some time they may grow larger, if other conditions are favorable to growth. This granulation of the ferrite is due to the fact that the original grains are broken down, and that the fragments form centers, or nuclei, for the growth of the new grains. It should now be plain that the change in properties resulting from cold working is due to the strained condition of the grains, and that to produce a strained condition in the grains, the working must be done at a temperature below that where annealing or grain growth takes place rapidly.

Hot Working: Because steel represents an aggregate, not a perfectly homogeneous material, annealing at 600° C., does not remove all the effects of the cold working. Thus, the pearlite, unless the steel is held at the annealing temperature for a considerable period of time, undergoes little change below 600° C., so the grains of pearlite remain in a strained condition at that temperature. To bring about a complete change in the structure and relieve all strains, the steel must be heated to some temperature well above 700° C. (1292° F.). The exact temperature depends upon the carbon content of the steel, and because of the nature of the changes that now take place, this temperature is called the critical temperature, or critical point. At this point the metal undergoes a complete transformation; it loses its magnetism and elasticity; it becomes stronger, but more ductile; it becomes a solid solution of carbon in iron; and its crystalline form changes from that described as having a body-centered cubic space lattice to the face-centered cubic form, the latter being similar to the former in shape but having, besides the eight atoms at each corner of the cube, six additional atoms, one of which is located at the center of each face of the cube. Iron in this latter form is called gamma iron to distinguish it from the former, which is known as alpha iron, while the solid solution of carbon and iron is known as austenite. Heating above this temperature, therefore, gives rise to an entirely new structure, and removes the strains from all the grains. Furthermore, if the temperature be raised to a point just above this critical, the maximum refinement of grain will be obtained, for no matter how large the grains

FIG. 112. Cast steel. Carbon .35 per cent. Magnified 100 diameters.

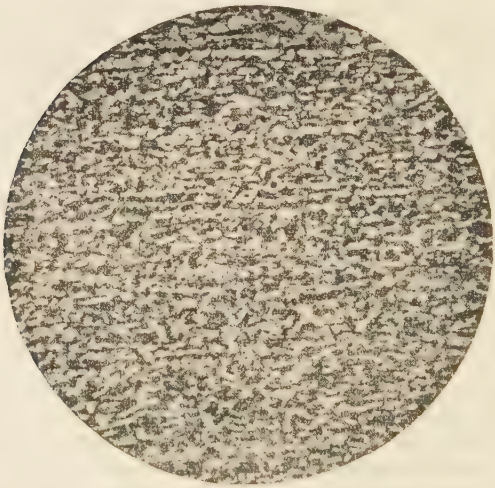


FIG. 114. Cold worked hypo-eutectoid steel. Carbon 0.30 per cent. Section of wire parallel to direction of drawing. Magnified 100 diameters.

FIGS. 112 to 115. Photomicrographs of Polished and Etched Specimens of Steel, grains of pure iron, while the dark areas are grains of the iron-carbon alloy.

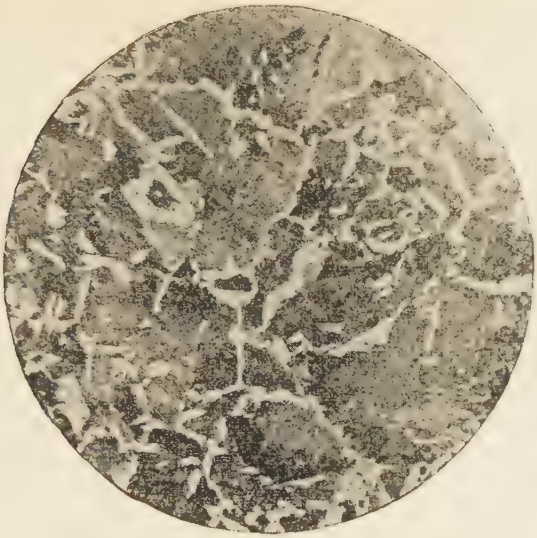


FIG. 113. Hot worked steel. Carbon 0.50 per cent. Finishing temperature high. From the center of a cross section of an 8-in. round forging. Magnified 100 diameters.

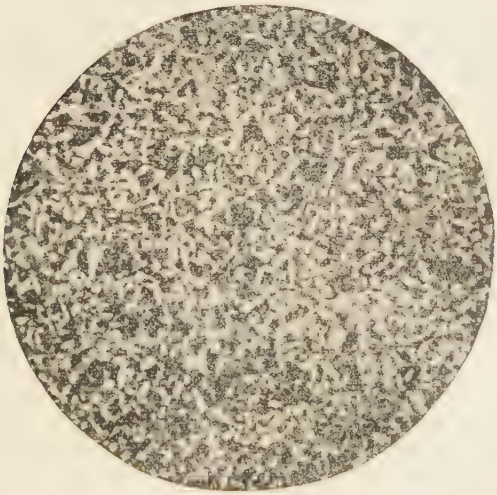


FIG. 115. Hot worked steel. Carbon 0.50 per cent. Finishing temperature low. Part of cross section of ¼-in. round. Magnified 100 diameters.

Showing Effects of Working upon the Grain Structure. The light areas represent or pearlite.

of ferrite and pearlite are, the grains of austenite will be of minimum size, because the transformation takes place at the lowest temperature at which austenite forms, and this condition is not favorable to grain growth. But if the steel be heated to a higher temperature, no further change in crystalline form takes place, but the steel becomes weaker and more plastic and the grains grow in size, apparently devouring each other in the process. And if the steel be mechanically worked, the crystals are deformed as in cold working, but the deformation is only temporary, for, owing to the greater molecular energy, the crystal fragments will at once form new grains, which in turn will grow rapidly to a definite size, corresponding to the temperature. Also, if the steel is now cooled normally, the size of the grains of the gamma iron determine the size of the grains of alpha iron, for, if the metal be cooled slowly, each grain of gamma iron apparently forms, at the critical range, a grain of alpha iron. The relation of the grain size to the temperature in this upper range is remarkable, and so constant that the practiced metallographer can estimate within twenty to fifty degrees the temperature at which the metal was worked, from observation of the grain size alone. Thus, it will be seen that working in this range may result in considerable grain refinement, the extent of which depends on the size of the section, the amount of work done on a piece, and the temperature at which the working is done, i. e., the finishing temperature. This grain refinement is one of the factors that determine the quality of the metal, for small grains in steel offer more resistance to deformation than large ones, so impart greater strength and toughness to the material. Since all strains produced mechanically at temperatures above the critical points of steel are immediately and completely removed, all working done in the range between these and the fusion points is to be considered hot working.

Heating for Hot Working: From what has already been said, it should be evident that, if, after a hot-working, the metal is heated above the finishing temperature, the grain refinement obtained by the working may be partly or entirely destroyed, depending upon how far above this temperature the second heating is carried. This fact should always be kept in mind, and should be considered most seriously in all cases where steel is to receive little or no working after reheating, as is often the case in fabrication or hot finishing operations. On the other hand, the reheating may be done so that the grain will be very fine without much working, for reheating to a point just over the critical will, in itself, refine the grain. Thus, the difference in grain size exhibited by Figs. 113 and 115 is not to be attributed solely to differences in the amount of work each has received nor to the finishing temperature, but also to the fact that the steel of Fig. 115 was reheated for rolling to a lower temperature than that of Fig. 113.

Hot Working the Ingot: Concerning the working of the steel in the mills, it is the general practice to begin the working of the ingot on

its initial heat, that is, before it has cooled much below the temperature of solidification after having been cast subsequent to its manufacture in the molten state. This practice is better than permitting the ingot to cool to atmospheric temperature and reheating, because the cooling, as well as the reheating, sets up internal stresses which are apt to cause cracks that will not be effaced by the working. These stresses are due to unequalized forces of expansion and contraction in different parts of the ingot, and can be avoided entirely only by treating the ingot in such a way that the change of temperature in the outer and central positions will be uniform. Needless to say, such a feat is very difficult to accomplish, after the ingot has once reached the temperature of the air throughout its mass.

Fiber Structure Produced by Working: From Fig. 114, used to illustrate the effects of cold working, it will be noticed that the grains are elongated in the same direction as the body itself, giving rise to a fiber-like structure that can be entirely removed only by heating the steel to a temperature somewhat above its critical point. It now remains to be pointed out that hot working, though the strain it produces in the grains is not persistent, also gives rise to a slightly fibrous structure from another cause. The factors contributing to this structure in hot worked steel are of the same nature as those responsible for the more markedly fibrous structure of muck bar, described under wrought iron. While steel does not contain nearly as much slag, oxides, and other foreign matter as wrought iron, it does contain some, and in addition some segregated materials and blow holes. The foreign matter, which, as will be shown later, is derived from several sources, is distributed through the ingot and is designated as **non-metallic inclusions.** In hot working, these inclusions, as well as the small bodies of segregated material and the blow holes, are all extended in the direction of the working, and appear in the finished material as lines or bands, which are referred to by the metallographer as **ghosts** or **ghost lines** or **ghost bands.** It is impossible to make steel absolutely free from these inclusions, and, fortunately, unless present in excessive amounts, they do little harm. They do, however, impart a fibrous structure to the steel, and this structure causes a directional difference in the mechanical properties. When the applied stresses act parallel to the direction of greatest elongation of the material, these fibers tend to, and actually do, improve the mechanical properties of the metal, but if the stress is transverse to this direction, the mechanical properties are apt to be inferior. This directional difference in properties can sometimes be lessened by the manner of working. Thus, in boiler plates, for example, it is overcome to a great extent by cross rolling the slab. But in cases where the elongation by hot working is great in one direction as compared with the spread, or elongation, in a right angled direction, it is almost impossible to form the article so that it will show the same values for the mechanical properties in all directions.

SECTION II.

SUMMARY OF THE HISTORY AND PRINCIPLES OF WORKING STEEL.

The Three Methods for Mechanically Working Steel: With reference to the manner of applying pressure to steel during mechanical working there are three possible methods; namely, hammering, pressing and rolling, all of which are extensively used at the present time. The shaping of steel by either of the first two methods is called forging. As an introduction to the study of the rolling of steel, a brief resumé of the history, principles, and effects of each of these methods will not be out of place and may be found quite interesting.

Hammer Forging: Hammering was the first method employed by man in shaping the metals. The first forging was done by hand hammers wielded by the workmen. The first power hammer, known by the name of tilt hammer, was built in England, and was a crude affair compared with the steam hammers now used. It consisted of a beam of wood hinged at one end and provided with an iron hammer head at the other. At an intermediate point, engaging cams on a revolving shaft alternately raised the free end and allowed it to fall on a bottom die fixed upon a suitable foundation. Thus the top die could be parallel to the bottom die in only one position, and the larger the piece to be forged the less power there was available to forge it. The first steam hammer was built in France in 1842. It consisted of a two-piece frame constructed so as to support, directly over a die, or anvil, a steam cylinder, to the piston rod of which was attached a tup, or hammer head. By admitting steam into the cylinder below the piston, the hammer was raised for a distance equal to the stroke of the cylinder, and then allowed to drop upon the anvil or bottom die. This hammer had the advantage of always keeping the top and bottom dies parallel, but was still lacking in one important particular. Its power being derived from the inertia of the falling tup, the hammer had the least power when it was most needed, that is, when pieces of large diameter or of great thickness were being worked. This fault in the single acting hammer was corrected by the invention of the double acting hammer, in which steam is admitted at the top of the piston and employed on the downward stroke as well as for lifting the tup. This type of hammer is illustrated in Fig. 187, page 635. The first double acting hammer was built at Midvale, Pa., in 1888.

Principles and Effects of Hammering: The principles of the hammer are that of an instantaneous application of pressure applied to a relatively small area. The strains set up in the metal are compressive and take place in a vertical direction in the region below the area subjected to the force of the blow. The crowding of the metal into one region, however, causes a small portion of the blow to be transmitted in horizontal directions. The suddenness of the blow tends to localize the effect and confine the refinement to the exterior. This fact results in a high degree of refinement, provided the amount of reduction is great or the section worked is a thin one, and is one of the reasons why it is possible to make some hammered material superior to rolled material. The resistance of the metal to deformation under shock, combined with the intermittant action of the hammer, makes shaping by hammer a slow process.

The Forging Press: The press is an English invention, dating from the year 1861. It was introduced into this country about the year 1887. It consists (see Fig. 181, page 623) essentially of a hydraulic cylinder supported by one or two pairs of steel columns which are anchored to a single base casting of great weight and strength. The ram of the cylinder points downward and carries an upper forging bitt vertically opposite a similar lower and stationary bitt which rests on the base casting to which the columns are attached. By admitting water under pressure to the cylinder at its top, the upper pallet is forced down upon the material to be forged, which rests upon the lower pallet. The pressure is applied slowly and is gradually increased to a maximum which may be maintained till the metal yields. By means of small auxiliary cylinders the ram is lifted after each application of pressure. The pressure exerted by the forging press is very great. In practice it is found that the lowest pressure that can be employed to be effective at a full forging heat is about 1.2 tons per square inch, but the pressures employed in actual work will often reach 13.26 tons per square inch.

The Effect of Pressing: The press differs very much from the hammer, both in action and the effects produced. Unlike the instantaneous application of the pressure as in the case of the hammer, the action of the press is so slow that a kneading of the metal takes place, and the strain, instead of being confined to the surface, penetrates deep into the material. An illustration cited by Messrs. Harbord and Hall will serve to demonstrate the difference in the effect produced by the two methods of working.[1]

"If tests are taken from the outer parts of a gun forging which has the center trepanned out, little difference is found in the strength of the material, whether the forging was done under the press or under the hammer, provided the latter was sufficiently heavy for its work; the press showing, if anything, slightly better results. If, however, the test

[1]See The Metallurgy of Steel. Vol. II. Page 855. Published by J. B. Lippincott Company, Philadelphia, Pa.

pieces are taken from the cores which have been cut out of the center of the forgings, the difference in the results is so very marked as to have induced all the best makers of heavy steel forgings to install presses in place of, or in addition to, their large hammers."

Advantages of the Press: Aside from its increased beneficial effect upon the material, the press has many advantages over the hammer, some of which it may be of interest to cite. The absence of shock in the press is a decided advantage both in the construction of the machine and in the working of material. The cost of working material under a press is less than with the hammer, because the output is greater, the press reducing faster than the hammer, fewer men and less skilled labor are required, and the fuel consumption per ton of output is less. A much greater proportion of the total work put into a press is transmitted to the metal than is the case with the hammer. Much of the energy of the latter is dissipated through being absorbed by the spring in the anvil block and by the earth. For certain work, however, this impact gives the hammer two advantages: first, it serves to remove scale; second, it enables the hammer to strike forgings in moulds with greater ease than the press. The difficulty of retaining water under the extremely high pressures required by presses gives the hammer an advantage, but this advantage is offset by its greater liability to breakage.

Rolling: Of all the known methods of shaping steel from the cast material, that of rolling, as introduced by Henry Cort in 1783, though perhaps not producing the best quality in certain classes of product, has come to be the most extensively employed. Though Cort is rightly credited with being the father of modern rolling, the use of this principle in shaping metals antedates his mill by many years. Thus, there are records to show that in the year 1553 a Frenchman employed rolls to produce sheets of uniform thickness for the stamping of gold and silver coin. In Sweden rolls were employed to produce certain steel sections prior to the year 1751, and even at that time the assertion was made that as much as twenty times more bars could be reduced in a given time than could be shaped under the tilt hammer of those days. This fact, coupled with the great efficiency of the rolling method, is responsible for the universal adoption of rolling as the favorite method of shaping. The rapid growth in production, due to the ever increasing demand for iron and steel, made it imperative that the most rapid method of shaping be employed. From the days of Cort to the present time, the rolling mill has kept pace with the growth in production and has passed through a surprisingly rapid process of development, not only in size and power but in design and in the shapes of sections turned out. This development, together with the introduction of numerous appliances for handling the material mechanically during the rolling, has multiplied the capacity of the mills many times. Some modern mills, like the rod mill, will now turn out a hundred times

as much tonnage in a given time as a mill of the same size and working on rods of the same size could have done fifty years ago.

Principle and Effect of Rolling: The process of shaping steel by rolling consists essentially of passing the material between two rolls revolving at the same peripheral speed and in opposite directions, i. e., clockwise and counter clockwise, and so spaced that the distance between them is somewhat less than the height of the section entering them. Under these conditions the rolls grip the piece of metal and deliver it reduced in section and increased in length in proportion to the reduction, except for a slight lateral spreading which is almost negligible in some sections. The extent of the spread will be found to depend mainly upon the amount of reduction and width of the piece. Thus in rolling plates, the total spread may be less than that of the first pass in the reduction of two-inch billets, especially if the percentage reduction in sectional area in the latter is great. The nature of rolling may be best explained by means of the following diagram.

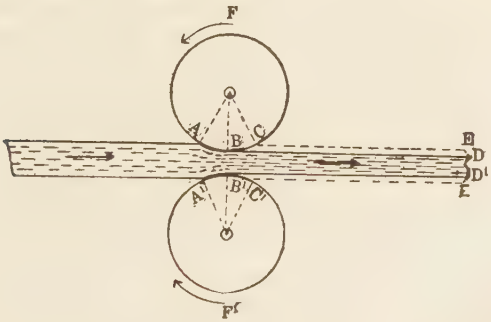


Fig. 116. Diagram Illustrating the Nature of Rolling.

Let O A C and O′ A′ C′ be two plain motionless rolls which are being forced into the bar AA′ E′E by means of pressures applied vertically from F and F′. The force exerted by the resistance of the bar will act along the radii of the rolls, as OA, OC, O′A′, and O′C′. The resultant of all these forces will be in the vertical lines O B and O′B′. Vertical compression of the metal will, however, occur only between the points B and B′. At all the other points between AC and A′ C′ the metal is forced away from the rolls and the bar is elongated. If now the rolls are made to revolve, the lower one in a clockwise direction and the upper in a counter clockwise direction, the piece is reduced in size and elongated as shown by figure A A′ D′D. This turning of the rolls introduces a second force, which acts in the direction of tangents to the arcs AB and A′ B′ and is equal to the force of friction and therefore proportional to the pressure between the rolls and the piece. The result of this force is to subject the piece to a

longitudinal pull in the direction of B to D, this pull being at its maximum at B and at its minimum at A. The compression, however, is at its maximum at A and its minimum at B. The net result of this double action is to cause the metal to flow forward so that the piece, reduced in size, is delivered at a higher velocity than the peripheral speed of the rolls, the evidence for which is found in the fact that the marks on the piece caused by a depression or elevation on the rolls is farther apart than the circumference of the rolls. A slight retardation of the forward speed of the piece on the entering side may take place, but this point has not been very well established as a fact.

Rolling Compared with Hammering and Pressing: It is a very difficult matter to institute a fair comparison between the effects of rolling with those of hammering or pressing. Each method has a field of its own with rather well defined boundaries. Thus, many shapes are so intricate in design that rolling them is out of the question, and so they must be formed under the hammer or the press. A crank shaft and a hammer head serve as examples of these classes of shape, which can be produced in no other way, unless by casting, when they would then be lacking in the strength, ductility and soundness imparted by working. That the hammer and the press are both under better control than rolls is evident, and being slower and more expensive to operate than rolls, these tools are used on material the cost of manufacture of which is a secondary matter. Hence, extraordinary care and attention is given to all phases of the working of forged articles. Rolls on the other hand are cherished for their speed, and tonnage is always a factor in rolling. There is, however, a small area in which the field of operation of all three instrumentalities overlap, as in the shaping of billets or blooms from ingots. In working these billets the different effects produced by the three methods become visible as the piece is shaped. When an ingot is hammered, the shape imparted to the section is very liable to look like A in Fig. 117. If the blows are light and delivered at high velocity, the upper surface only will be elongated as shown at B in the figure. These facts show that the impact is almost entirely absorbed by the surface of the metal, and to obtain the best effect from hammering it is necessary to continue the work until the section has been reduced to one of relatively small size. The deeper penetration of the work of the press is shown by the rounded corners of the section represented by the figure at C. Any cavity at the center of the piece is closed under the action of the press, whereas the tendency of the hammer would be to enlarge it. The effect of rolling is influenced very markedly by the temperature. In the first place the temperature, in order to secure the greatest efficiency from the rolls, is likely to be higher than that required for either hammering or pressing. In a piece uniformly heated, the flow of the metal is slightly faster at the two surfaces than in the center in the smaller sections, while in larger sections the flow at the surface may be very much greater. The effect of the additional plasticity imparted by even a slight rise in tem-

perature upon the flowing properties of the metal is plainly visible in the results obtained in rolling ingots under the two conditions as illustrated by the figures at D and E. The fishtailing of the piece represented at D shows that the flow of the metal is faster at the surface due to the lack

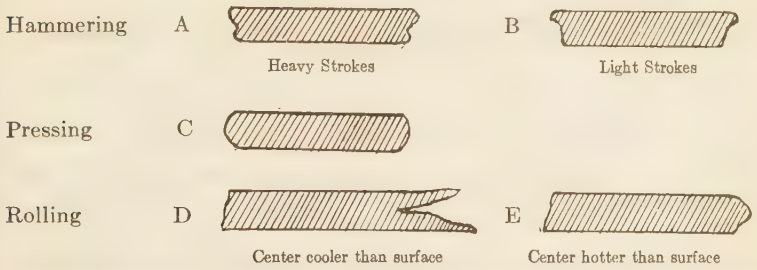


Fig. 117. Diagram Illustrating the Effects of Hammering, Pressing and Rolling.

of plasticity at the colder center. The reverse of these conditions is shown at E with the corresponding difference in effect. In this case the effect of the working has penetrated to a much greater depth and extent than in the previous case. The amount of draught and the speed of rolling are also important factors in producing these effects, a more thorough discussion of which will be taken up later.

Rolling and Pressing Ingots: The notion most prevalent among steel men, however, is that the tendency of rolling is to produce a more superficial effect than either hammering or pressing. That this notion is correct with respect to pressing is indicated by the precautions taken in casting large ingots for armor plate that is to be rolled. Figure 118 shows the difference in shape of ingots for the press and for the rolls. The concave and diamond shaped sides of the ingot for rolling are formed to prevent the loss due to fishtailing, as already explained. Under the press the two surfaces of a square sided ingot are slightly rounded, but, in rolling, a square sided ingot would make a concave sided plate which in many cases progresses to such an extent as to cause actual overlapping. It is admitted by nearly every one, however, that, with very slow rolling and carefully regulated temperature, the quality of rolled material may be made the equal of that reduced under the press.

Fig. 118. Shapes of Ingots for Pressing and Rolling Armor Plate.

CHAPTER III.

ESSENTIALS OF ROLLING MILL CONSTRUCTION AND OPERATION.

SECTION I.

THE ROLLS—THEIR PREPARATION AND ARRANGEMENT.

Parts and Equipment of the Simplest Type of Rolling Mill: After the rolls, themselves, two in number in the simpler types of mill, the next most essential part of the mill are the **chocks** or bearings which support the ends of the rolls and permit them to be turned without displacement. The chocks in turn are kept in place by means of the **housings,** which together with the adjusting screws also furnish a means by which the distance between the rolls is regulated. These parts constitute **a stand** of rolls. The housings are bolted to **shoes** which rest upon a firm foundation, to which they are always securely bolted. Next in importance are the parts which connect the mill with the driving shaft. First, there are the **spindles** that transmit the power from the pinions to the rolls, to both of which they are connected by means of loosely fitting **coupling boxes.** The **pinions,** supported in housings similar to the roll housings, are gears, one of which is driven through a driving spindle in line with one of the rolls. They serve to impart opposite motions to the rolls. The last part of equipment essential to the mill is the prime mover, which in modern mills may be a steam engine or an electric motor. As to other equipment, reheating furnaces are first in importance. Large mills must also be provided with **roll tables** for handling the material. A discussion of the driving apparatus is an engineering subject which lies beyond the intended scope of this book and will receive no further mention here. All the remaining parts, however, should be studied somewhat in detail. They are fully illustrated by Fig. 127 (page 487), Fig. 132 (page 497) and Fig. 168 (page 587).

The Rolls and Their Parts: Of the essential parts of the rolling mill, the rolls furnish a subject of great interest. There are three parts to a roll; namely, the **body,** which is the part on which the rolling is done; the **necks,** or the parts which rest in the chocks and furnish the surface upon which the pressure is applied for reducing the size of the piece; and the **wobblers,** one at the outer end of either neck or of both necks, which are formed by notching the prolongation of the neck of the roll. Over the wobblers the coupling box for driving the roll is fitted. In the case of plain rolls, such as are used for rolling plates and, in part, for other flats, these are the only parts of the roll. In the case of rolls for other material, **grooves** are cut into the surfaces of the rolls to form the section required.

A groove in one of the rolls or a combination of grooves in the two rolls, which at the line of contact forms an opening corresponding to the shape of the section desired, is called a **pass.** The three most common passes are shown in the accompanying figure.

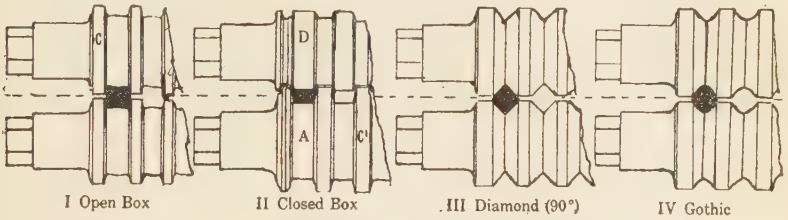


FIG. 119. Showing Different Types of Passes for Roughing and Semi-finishing Mills I, III and IV are spoken of as **open passes** while II is called **a closed pass.** In the closed pass the piece is buried in one of the rolls so that three sides are enclosed by the groove A, the fourth side being closed by the tongue or former D, on the other roll. **Collars** are represented at C and C¹. Passes I and II are commonly spoken of as **box passes,** while III is called the **diamond pass,** and IV the **Gothic pass.**

The Manufacture of Rolls is a separate industry, and the art of roll-making is not widely known even among the users of rolls. When the work the rolls have to do is considered, together with their effect upon the product of the mill, the importance of good rolls is better appreciated. Most rolls are castings, yet they must be ductile to withstand the shock produced as the piece enters them; strong to resist sufficiently the great pressure applied to their ends; hard to give them good wearing qualities; and sound, so that they may not develop surface defects which would leave their marks on every surface rolled on them and cause the material to be rejected. To secure these qualities the best of materials and the greatest of skill are required in their manufacture. The materials are of three kinds, namely, cast iron, steel and alloy mixtures. From these materials four kinds of rolls are produced. They are known as **sand rolls,** which are made of pig iron; **chilled rolls,** also of cast iron; **steel rolls,** made of steel by casting; and **"adamite" rolls,** which is a trade name for a metal produced by mixing steel with pig iron containing certain percentages of chromium and nickel, or by mixing steel and the ferro alloys of these elements with the proper amount of an ordinary pig iron of high grade. As an example of how rolls are made, some of the processes as carried out by one of the leading manufacturers of rolls will be briefly described.

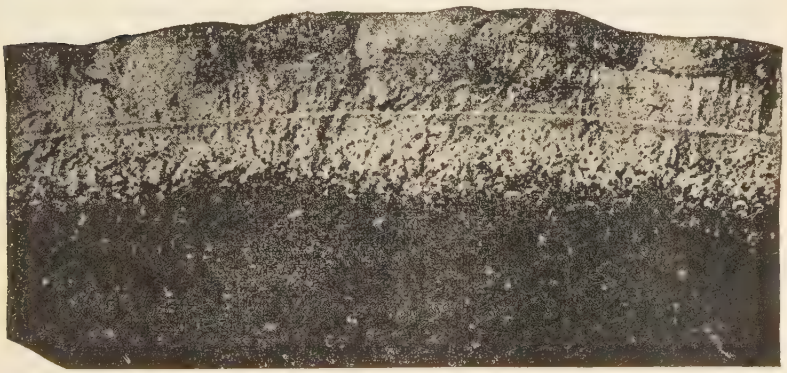
The Sand Roll: Sand rolls are cast in a sand mould. The sand used is a loamy sand of a special kind obtained only from deposits left in old water courses. This sand contains sufficient clay intimately mixed with the silica to form a firm bond and yet be refractory enough that it will not fuse at the temperature of the molten iron. The mould is prepared by ramming this sand, moistened a little, into a half flask, and then sweeping

the sand from the half flask with a sweep, the outline of which is similar to the contour of the roll. Two such half flasks are required for each roll, each one containing one-half of the roll divided longitudinally. After sweeping and smoothing, the half moulds are coated inside with a plumbago or other carbonaceous dressing and carefully dried. Just before casting, these two parts of the mould are firmly clamped together and are set in a vertical position for pouring, for which purpose a casting pit is provided for large rolls. Thus, one end of the roll forms the bottom of the casting, the other end the top. The top is capped by a cope to provide a deep sink-head, which is cut from the roll after casting. The gating to the mould enters the flask at the bottom neck of the roll and on a tangent, so that a swirling action is imparted to the molten metal as it rises in the mould. In this way all dirt and other foreign matter is forced to the center, which condition insures the outer portion of the roll will be composed of clean metal.

The Materials Used in Sand Cast Rolls are charcoal iron and roll scrap. The mixtures are melted in coal fired reverberatory furnaces. The bath, sealed off from outside air, is separated from the grate by a bridge wall, over which a non-oxidizing flame sweeps and furnishes the heat for melting. In the melting a little carbon, silicon, and manganese are removed from the metal, and by the time the charge is melted a highly silicious slag has formed, which protects the metal from any further action that might be produced by the flame. As soon as the metal is melted, fracture tests are taken, by means of which the metallurgist in charge is able, from long experience, to determine when the bath is of the right composition to produce the kind of roll desired. The molten metal is tapped from the furnace into a small tilting ladle, which is carried by overhead crane to the moulds, and the metal is poured into the gate over the lip of the ladle. The pouring is very rapid and must be continuous, as the slightest interruption would ruin the casting. After the metal has solidified and cooled sufficiently, the mould is removed, and the roll is cleaned of the adhering sand, when it is ready to be machined to the size and shape required.

Chilled Rolls: Rolls of the chilled type are made up of three layers of metal, each of which represents a type of the same original metal. The interior of these rolls is composed of grey iron, which is enclosed by a cylinder of mottled iron, and outside of this a similar layer of white iron, called the **chill.** This composite structure is procured by taking advantage of the peculiar properties exhibited by pig iron on cooling from the molten state. In this state iron holds in solution all the carbon which it contains at a given temperature. In cooling some of this carbon separates in the form of crystals of graphite, which is distributed throughout the mass; the remainder is spoken of as combined carbon, the effect of which is to increase the hardness of the metal. The separation of the graphite depends mainly upon the rate of cooling, so that if the iron is cooled very suddenly

all the carbon may be retained in solution as combined carbon, which renders a chilled iron that is dense, white, intensely hard, and capable of receiving a very high polish. In making these rolls only the body of the roll is given a chill. This chilling of only a part of the roll is effected by making that part of the mould corresponding to the necks and wobblers of sand, while that part destined to form the body is made up of a heavy cast iron ring, usually built up in sections which are carefully turned at the joints and bored out true inside. After giving the inside of the mould a coating of the carbonaceous wash, they are warmed to remove moisture,



The line in the cut marks the limit of clear chill. When depth of chill is designated, it is assumed to mean clear chill.

FIG. 120. Method of Measuring Depth of Chill on Rolls.

then assembled, and the casting is made as for sand rolls. The rapid cooling, caused by the absorption of the heat by the cold casting in contact with the molten metal, causes the chill on the outer surface of the roll, the depth and hardness of which is controlled by varying the composition of the molten iron. Chilled rolls, once they are formed, cannot be softened or hardened by heat treatment, as such treatment would cause part of the carbon to separate as graphite and destroy the chill. A patented chill is now in use. It is made in the form of a ring composed of segments of solid metal on the inside and a water cooled ring on the outside. This construction has the effect of causing the mould to become smaller as it is warmed by the heat from the molten metal, thus subjecting the roll to a high pressure, which is said to give a more even chill and a denser and tougher material than the common chill. The chill is measured by

the least depth of clear chill as shown in the accompanying photograph, while the analysis of each of the three regions here depicted is given in the following table:

Table 57. Analysis of Different Parts of a Chilled Roll.

	TOTAL CARB.	COMB'D. CARB.	GRAPH. CARB.	SIL.	SUL.	PHOS.	MANG.
Chill.....	3.00	3.00	....	.90	.04	.200	.25
Mottled.....	3.00	2.25	.75	.90	.04	.200	.25
Grey.....	3.00	1.00	2.00	.90	.04	.200	.25

Difficulties in Making Chilled Rolls: The greatest of skill and experience are required in the making of chilled rolls. The process of chilling causes the different parts of the roll to cool at different rates and sets up stresses in the casting which make it liable to crack and break. The range of temperature at which the metal may be poured is very narrow, while a very slight change in the chemical composition of the metal will sometimes produce a marked effect upon the chill, changing both the depth and the hardness. The size of the roll also affects the nature and extent of the chill. Besides, the roll in use is subject to great pressure, uneven stresses, uneven heating, over heating, and sudden cooling, all of which tend to cause the chill to crack and spall. This tendency to spall is overcome by the manufacturer to some extent, but careful handling of the roll in use is essential also. Large rolls are especially difficult to cast properly. The largest chilled rolls are made for rolling plates, and a very tough chill is required. The chills for one of the largest of these rolls weighs 105,000 pounds and the roll itself requires 80,000 pounds of metal to cast it, while the total length of the mould is twenty-three feet. A large percentage of these rolls are lost in casting, due to the cracking of the roll at places where the different sections of the chill are joined. Small chilled rolls are used in guide, rod, hoop and bar mills, and for a variety of purposes, but chilled rolls for shapes are very difficult to make owing to the fact that the collars in such rolls are liable to bind in the chill and crack off. All these factors tend to make chilled rolls very expensive, but a much greater tonnage is obtained from them than from any other kind, and their use is imperative where a very fine finish is required to be imparted to the product.

Steel Rolls are cast in sand in much the same way as sand rolls. In this case, however, ganister sand mixed with a little fire clay to act as a bond is used, because the higher temperature of molten steel will heat any but the most refractory sands to their fusion point. Steel rolls are stronger and more ductile than sand rolls. The deflection of a steel roll under a given load is only about half as much as that of a common sand roll. Besides, they may be annealed, when they become almost unbreakable. They cannot be permanently hardened, because any hardening by heating and quenching is removed by contact with the hot metal, the heat from which produces the same effect as a drawback. On account of their

unavoidable softness, then, steel rolls do not wear well, and hence cannot be used on finishing stands. For blooming mills and roughing stands of other mills where great strength is required, these rolls are invaluable, and they are used in such stands almost exclusively. Occasionally, where a good finish on the product is not required, steel rolls will be used on the finishing stands. The material used is, for the most part, acid open hearth steels varying from .40 per cent. to .65 per cent. in carbon content. When steel rolls are used for finishing, the carbon content is increased to .85 per cent., and sometimes to as high as 1.25 per cent.

Other Rolls: In an attempt to overcome the defective softness of steel rolls and at the same time retain their great strength and toughness the alloyed mixture previously referred to as "adamite," has been developed. These rolls are being used with considerable success, and seem to hold promise of even greater efficiency. Forged steel rolls have also been tried and found to be very satisfactory, but their high cost prohibits their use except where exceptional strength is required.

The Size of Rolls: In length of body, rolls vary from one to seventeen feet, and in diameter from seven to fifty-four inches. The largest rolls are used on the plate mills, the smallest on the small hand guide mills. On account of the smaller surface exposed to pressure, small rolls cut into the metal with greater ease than large ones and so require less power to do the same work. Therefore, the heavier the rolls, the heavier must be the machinery throughout the mill. The factor most important in determining the size of the roll is that of strength, and for the sake of safety rolls as large as practicable will be employed; first cost is of secondary importance. The resistance of a plain roll to transverse stress is proportional to the cube of its diameter, and inversely proportional to the length of its body. The diameter of the roll at the base of the deepest groove determines the strength of a grooved roll; so, for grooves of the same depth, one set of rolls may be many times stronger than another only one or two inches smaller in diameter. The size of rolls is expressed by writing the diameter and the length of body in inches, with the × sign between. Thus 42″ × 60″ means that the roll is forty-two inches in diameter and sixty inches long in the body.

Roll Design: Designing the rolls was originally one of the duties of the mill superintendent, the roll turner or the roller, but the demands upon the mills in the way of new sections made it necessary to place this work in the hands of men specially trained to the work, so that, now, roll designing is a distinct profession. There are few rules in the trade, and the roll designer must depend mainly upon experience for guidance. It is seldom, therefore, that two roll designers will be found to develop a section in precisely the same way. That exceptional ingenuity and extreme resourcefulness are required in this profession is attested by the wonderfully intricate shapes these men are turning out, and that, too, with the most astonishing accuracy.

Methods of Procedure in Designing Rolls: Given a new section to evolve, the roll designer proceeds in some such manner as follows:—From a drawing of the section, if he has decided it is one that can be rolled successfully, he will have a templet made of the exact dimensions of the section, and from this templet another for the finishing pass in which an allowance of about .015 inch per inch of dimension of the finished piece is made for contraction of the metal in cooling from the finishing temperature to atmospheric temperature. He must then decide on the proper size of rolls to use, which determines the mill that is to roll the section. This decision made, he has given the approximate size of the billet or bloom from which to begin, the number of sets of rolls, and the number of passes in which the work must be done. Having given, now, the first and last passes with their dimensions, and the total number of passes, he may begin the design of the intermediate passes. This he does by drawings which are begun by setting off a "construction line" or "pitch line" as it is sometimes called. This line locates the center of gravity, or the center of figure, of the various passes and is usually placed midway between the axis of rotation of the two rolls.

Difficulties in Designing Rolls: Having drawn the pitch line, the roll designer then proceeds to mark off the passes from billet to finishing pass, and in doing so he has a multitude of things that must be kept in mind, some of which are: 1. The method of shaping is one of squeezing, spreading, and bending. 2. The total amount of reduction is best distributed among the various passes as evenly as possible, excepting the finishing, which is reserved to true up the shape. 3. All sides of the piece should be thoroughly worked. 4. The piece should not enter two successive passes in the same position, as otherwise the metal will be squeezed out between the rolls and form what is known as a fin. 5. Since they weaken the roll very much, deep cuts into a roll should be avoided. 6. The passes should be so shaped as to eliminate side thrust on the rolls. 7. The dimensions must be closely controlled. In box-passes and passes of a similar type, the piece will not enter the rolls if it is larger in all of its dimensions than the pass. In some passes, such as those used in diagonal rolling, the piece may be larger than the pass in any direction, but it must be properly proportioned to avoid over-fills and fins. 8. The thin parts of a section cool faster than the heavier parts, and must, therefore, be formed in the last passes. 9. Sections that require deep grooves in the rolls are difficult to roll successfully on account of the difference in the peripheral speed of the bottom and the top of the groove. The part of the roll having the greatest diameter elongates the piece more rapidly than the part having the smallest diameter and tends to cause the piece to twist and curl on leaving the rolls. This difficulty can be overcome by using rolls of slightly different diameters, by raising or lowering the center of mass of the piece from the pitch line, or by reducing the amount of reduction on the part that elongates the more rapidly. 10. The

draught on the various parts of a section must be properly proportioned, as otherwise the piece will contain waves or be distorted in other ways. 11. He must also keep in mind that all kinds of steel do not work alike, and what can be done with open hearth steel, for instance, would be impossible with Bessemer and vice versa. With these difficulties to contend with, even highly experienced roll designers may fail on the first trial at a new section. In that case an entirely new set of rolls may be required, which adds much to the expense of rolling the section. Besides questions, such as those above, that affect the shaping of the material, the roll designer is also expected to consider time and cost. So, he will endeavor to avoid roll changes or other operations that will delay the work or add to the cost of the rolling operation. Thus, it will be found that in most mills one set of roughing rolls will be used to produce a great number of different sections. This has the effect of giving the designer a fewer number of passes with which he forms the shape, and adds much to the difficulty of his task.

Turning the Rolls: Having designed all the passes for the rolling of a given section, a set of templets, one or more for each pass, is made. These templets are to be used in turning the roll, for which purpose a special set of tools may be required. In the roll shop, the rolls are first centered. Various methods may be used for finding the center. When this point has been located, a lead hole may be made with a ratchet drill, and then widened out to the proper angle with a reamer to a depth of about $\frac{3}{4}$ inch. The roll is then placed in the necking lathe, when, supported by the center holes, the necks may be turned to exact size, or they may be machined to near the exact size and finished by grinding and polishing. Since the center holes are liable to wear down irregularly if used throughout the process of turning, the body of the roll is turned in another lathe in which the roll is supported by chocks that fit the necks. Here the roll is turned down to size, and the passes cut in to fit the templet supplied by the roll designer. When one roll is completed, it is placed in chocks higher up in the housing, and the second roll is placed below it, where it may be turned with the finished roll as a guide, so that the two parts of the passes may be made to fit exactly. With ordinary tools, chilled rolls are seldom turned with a surface speed of more than fifty-six inches per minute, but with tools made of high speed tool steel this speed may be increased to seventy-two inches per minute. Speeds twice as great as these may be employed for turning the other kinds of roll.

Dressing the Rolls: After a set of rolls has been in service a variable length of time, the passes become worn to such an extent that they no longer produce the section to the required dimensions, and they must then be replaced by another set. In most cases these worn out rolls may be turned again, or dressed down, so as to give the correct size once more, or if the section is of such shape that this refitting is impossible, the passes may be

enlarged to produce a section similar in shape to the first one but of greater weight. This wearing of the rolls is one reason why rolling tolerance is required on all materials.

Types of Mills: Before proceeding farther it may be well to explain that there are two main types of mill, referred to as **Two-high** and **Three-high** mills. As the names indicate the classification is based on the manner of arranging the rolls in the housings, a two-high stand consisting of two rolls, one above the other, and a three-high having three rolls thus arranged. In all three-high mills, each roll revolves continuously in one direction only, whereas in two-high mills the direction of the rolling may be in one direction only, or in opposite directions at different intervals, in which case they are called **reversing** mills.

In the old days before the invention of the three-high mill or the reversing engine, if it was desired to pass the bar more than once through the same stand of rolls, the catcher returned the piece to the roller by placing it on the top of the upper roll, which carried it in the direction opposite to that in which it moved at the bottom of the roll. Mills in which this practice prevailed were called **pull-over** or **drag-over** mills and are to be looked upon as the fore-runner of the reversing mill. In the first mill of the reversing type a ratchet gear furnished the means for reversing the mill. Pull-over mills are still in use, and are the mills most often employed for rolling sheets. Another kind of two-high mill is the **continuous** mill, which consists of several stands of rolls arranged in tandem and propelled with a single engine. **Guide, loop** and the so-called **cross country** mills are made up of several two-high stands and one or more three-high stands. Guide mills are small hand mills consisting of several stands of rolls in a train. They take their name from their having metal guides to support the piece as it enters the various passes. In many guide mills it is the practice of the catchers, in order to save time, to start the piece through each of the passes before it is through the preceding one, thus forming a loop. Hence, the **looping mill.** After the institution of this practice it was found that the loop could be made by means of a tube or trough, called a **repeater,** and thus dispense with the catchers. Such a contrivance is a part of many modern bar and strip mills. The cross country mill is made up of several stands of rolls, arranged in trains or trains and tandem sets. The bar, propelled mechanically by means of live rolls, transfers, etc., must reverse its course two or more times to pass through the various sets of rolls from the furnace to cooling tables. These mills represent one of the latest and most efficient types. **Combination mills** are those in which the roughing or major part of the reduction is done in continuous rolls and the shaping in a guide or loop mill. **The universal mill** is one, which, in addition to the horizontal rolls, usually arranged two-high but occasionally three-high, is provided with vertical rolls, all set in one housing. These mills originally contained but two vertical rolls on one

side only of the horizontal rolls, but in modern mills there are two sets of vertical rolls, one set on either side of the horizontal ones. The mill is used for rolling plates and eye bars that require rolled edges. Besides these types, there are many special mills, usually named from the inventors, such as the Gray mill for rolling beams and H-sections; the Wenstrom mill, a kind of universal mill for rolling bars; Sack's mill for rolling shapes, also a development of the Universal mill; and the Schoen mill, which rolls car wheels. Opportunity will be given later to become better acquainted with most of these mills.

SECTION II.

PARTS OF THE MILL ESSENTIAL TO THE OPERATION OF THE ROLLS.

The Chocks: As previously indicated, the chocks furnish the bearings in which the necks of the rolls turn. They are usually made in two parts. The surface in contact with the neck is made of brass, bronze, or white metal, which can be replaced as necessary. The use of these alloys is necessary in order to reduce friction, which is much less between metals of different kinds, due to difference in size of the molecules or grains, and to the tendency of the softer metals to flow. The approximate composition of some of the more common of these alloys is given in the sub-joined table of analyses.

Table 58. Composition of Bearing Metals.

Name of Alloys	% Copper	% Zinc	% Tin	% Antimony	% Lead
Red Brass.....	85	15	..	.....	.....
Yellow Brass....	65	35	..	.....	.....
Bronze, No. 1...	85	.	15	.....	.....
Bronze, No. 2...	82	15	3	.....	.....
White Metals....	0 to 6	..	10 to 15	12 to 20	65 to 80

Since 1915, a new white metal composed of lead, about 98.5 per cent, and sodium, about 1.5 per cent, has been used, but with varying success. As all these metals are soft and not very strong, it is necessary to carry them in castings, which are set into the housings. These castings are box-like in shape, each one containing on one side a semi-circular groove corresponding to, but larger than, the necks of the rolls. In order to reduce their weight, they are cored out, and may be made of either iron or steel.

The Arrangement of the Chocks in two-high mills is a simple matter. Two chocks under the necks of the bottom roll, and two similarly placed above the top roll furnish the main bearings. In case the top roll is adjustable, light bearings must also be placed under its necks to make it possible to support this roll. In the heavy mills hydraulic jacks or balance weights, placed under the mill, are connected by vertical rods to the lower chocks and serve to lift the roll as desired; in the small mills, screw bolts extending through the housing serve the same purpose. The exposed half of the neck of the lower roll will usually be covered to protect it from

scale, etc. The arrangement of the chocks in three-high mills is more difficult. The simplest way is to place double groove chocks between the top and middle and the middle and bottom rolls, and then set them in the housings one above the other, so that all the adjusting made necessary by the wearing away of the brasses and the material of the rolls, themselves, may be made with the large set screws in the top of the housing. But this arrangement causes the bottom bearing to wear down rapidly and increases the power required to drive the mill, due to the additional friction induced on this bearing by the weight of the two upper rolls and their chocks. This fault may be overcome in two ways: (1) By making the bottom roll fixed and supporting this extra weight on the shoulders of the chocks themselves, the distance between rolls may then be regulated with shims, or "liners," by adding or removing the shims as the bearings wear down. (2) A better way, and the one most often employed in modern mills, is to make the middle roll fixed, in which case the bottom roll is raised and lowered by means of an adjusting wedge attached to a screw in the housing which permits it to be moved back and forth with a wrench from the outside of the housing. Other methods of adjusting this roll are in use also. A method of supporting each roll separately by means of hooked screws and cross bars has also been developed, the details of which would be unprofitable to study here. In all mills, two-high as well as three-high, the top chocks are held down by means of two strong screws which work in threaded holes or nuts in the tops of the housings.

The Function of the Chocks is not only to furnish bearings for the rolls vertically but to prevent their movement laterally as well. This lateral displacement of the roll is prevented by the inner edge of the bearing which is formed to fit against the shoulder of the roll. Adjustments for wear in this direction are provided for by adjusting screws which extend through the side of the housing and bear on the ends of the chocks. This lateral adjustment is a matter of great importance in rolling sections that require grooved rolls, the reason for which is self evident.

The Housings: There are two housings for each stand of rolls, they may be made of either iron or steel, the choice of materials depending upon the size of the mill, the strength required, and the preference of the management. They are castings of an O-or U-form, each enclosing a space, called the **window,** which serves as a receptacle for the chocks. Housings may be either **closed topped** or **open topped;** in the former, the base, the two legs, and the top are all cast in one piece, while in the latter the top may form a separate part which can be removed. The base of the housing is cast with a projection on each side, the two forming the feet of the housing. In the bottom of each foot is cut a groove which fits over a girder, called a **shoe,** running parallel to the rolls. Suitably shaped bolts then serve to clamp the foot of the housing to the shoe, which is firmly fastened to the foundation by means of long bolts. This method

permits the housing to be moved laterally, and much facilitates the plumbing and lining up of the mill. The tops of the two housings in a set are prevented from spreading apart by means of suitable tie rods, or the tops of both housings may be cast in one piece. Similarly, tie rods will usually be placed at the bottom. Recesses or other openings are cast in the inside of each housing to receive the supports for the guards and guides, these supports being usually in the form of square bars which extend from housing to housing in front of the rolls. The immense pressure applied to the rolls between the top and bottom of the housing acts as a stretching force on the uprights of the housings, and is an important factor in determining the reduction that can be effected in one pass and also the exactness with which the thickness of the piece is controlled.

The Adjusting Equipment for the rolls has already been located and partly described in the preceding paragraphs. In addition it should be pointed out that in large mills, in which the top roll is adjusted during the rolling, power must be supplied to operate the screws. To provide for the transmission of the power, the top part of each screw, which is made square or hexagonal for a distance slightly greater than the rise of the roll, passes through the core of a pinion. These pinions may then be turned directly or indirectly with a horizontal hydraulic cylinder located at a proper height, usually on top of the housings of the driving pinions; or, by means of a worm shaft and the proper worm gears, the screw down may be effected with a small electric motor. In small mills where the adjustment is only occasional, the screws will be operated by hand by means of spanner bars. In all cases the compression of these screws is unavoidable, and, combined with the stretch of the housings, produces the spring of the mill, which in some cases is surprisingly great.

The Pinions: An important part of the mill is the pinions. They are broad faced steel gears located between the prime mover and the rolls. Their functions are to divide the power, which is delivered by the engine or motor through a single shaft or driving spindle, usually spoken of as the leading spindle, among the rolls and to control their direction of rotation. They run in bearings contained in a pair of housings similar to those for the rolls, and should be completely and tightly covered to protect them from dust and dirt which would cause them to wear out rapidly. They need to be well lubricated, and the present practice of giving them an occasional dressing of pine tar, plumbago, and tallow, or other mixture of grease, is giving way to the better plan of having the housings cast in one piece so as to form an oil bath at the bottom in which the bottom pinion is partly submerged. Pinions are of three kinds, based on the arrangement of the teeth. In the oldest form the teeth ran straight across the face, but eventually it was found that a smoother running pinion results if the face be divided into two parts and the teeth of the two halves staggered, i. e., set in so that the teeth in one-half are in line with the space in the other. This design gives an effect like that which would be obtained if the pitch

were decreased. This scheme was also found to effect a saving in power. Still another improvement results from the use of pinions with helical or "herring bone" teeth, which also tend to eliminate vibration in the pinions, as some parts of the teeth are always in contact, thus making the transmission of the power continuous. This presence of jar when each tooth comes into action has an effect on the material, as in certain classes of material the old form of pinion was found to produce marks on the bar by the jarring of the teeth meshing being transmitted to the rolls. In all mills except plate mills, the distance from center to center of the pinions determines the size of the mill.

The Connections: Each roll, except in the case of friction driven rolls, is connected to its pinion by means of **spindles.** They are usually made of cast steel and are fitted at each end with wobblers like those on the rolls. The connections between pinions and spindles and rolls and spindles are made with **coupling boxes.** The coupling box is a hollow cylindrical casting, the space in which corresponds in section to that of the wobbler, one end of the box fitting over the wobbler on the roll and the other over that of the spindle. In order to safe-guard the mill, the coupling boxes are usually made the weakest part of the mill. In some mills this weak spot is the leading spindle, which connects the pinions with the engine or motor, instead of one of the coupling boxes. Since the spindle must be put in place with the two coupling boxes on it, the length of the spindle must be a little more than twice the length of the box. In mills, the top roll of which moves up and down through a great distance, the upper spindle is thrown out of line horizontally. As it is very difficult to operate with a spindle more than 15° out of level, this angle must be kept within the allowable limit by increasing the length of the spindle. In such cases the ends of the wobblers are cut from a section of a sphere to give them the rounded form necessary to permit them to work at different angles, and the spindle is supported by means of saddles which rise and fall with the roll and hold the spindle in place.

Guides and Guards: In order to prevent collaring and to insure that the piece enters and leaves its pass in the correct position, guides are employed. These guides vary in form and size to fit the conditions. In some cases they are merely grooved fore-plates; in others they are blunt edged plates set up in front of the collars, dividing the space in front of the rolls into a series of pigeon holes; in large mills rolling heavy sections, they may take the form of grooved rollers; in the smaller mills like the guide mills, they are trumpet shaped castings that fit close up to the roll and have exit openings to conform to the shape and size of the section of the entering piece; in other mills, like the continuous mill, they may be so constructed as to twist and thus turn the piece between two successive passes. Guides may be employed on both sides of a pass, in which case they are designated as entering guides and delivery guides. They are held in place by means of the rest bars previously mentioned in connection with

the housings. Guards are devices employed mainly on the delivery side of the mill to control the direction of the piece after leaving the pass. Reversing and three-high mills will be provided with guards on both sides of the mill.

Additional Equipment: In addition to the parts of the mill already described, every mill must be provided with suitable appliances for heating and handling the materials and disposing of the product. The various furnaces for the heating of the raw materials will be described later. As to the handling of materials, it is evident that reliance on man power places such restrictions upon the size and output of the mill that, in the case of certain small mills and of all the larger mills, the appliances for handling the materials mechanically are to be considered as essential parts of the mill. The number of these appliances is so great and the kinds are so varied that a detailed description of all of them is impossible, and since it would be unprofitable to describe only a few forms, little more than an attempt to mention some of the more important ones will be made here. For getting heavy material in and out of furnaces and delivering it to the mill, electrically operated **charging and drawing machines** are used. These machines are of two general types, namely, those that travel on overhead tracks and those that move on a track laid on the mill floor. For handling material during the rolling process, roll tables are provided for large mills, while various forms of appliances, called repeaters, are used on small mills. Roll tables consist of a frame work and a number of rolls, which may be rotated at will, mounted thereon. For operating these rolls, the steam engine has been replaced by the electric motor in all new mills and also in most of the old ones. Roll tables may be either stationary or movable. Movable tables, often used on three-high mills, may be of the **tilting,** the **lifting,** or the **traveling** type. Tilting tables are mounted on an axis of rotation, which may permit one or both ends, depending on the location of the axis, to be raised and lowered, whereas lifting tables always remain in horizontal positions and may be moved up-and-down or up-and-down and side ways. Traveling tables, which are now to be found only on the old mills, move along on tracks laid on either side of a roll train, and may be of the tilting type also. After the rolling, **cooling beds,** of which there are many types and forms in use, must be provided to receive the material from the mill. The straightening of the material, which irregularities of the rolling and cooling often makes necessary, is done in roll, or machine, straighteners or by means of gag presses. In order to keep up with the mill only the most rapid methods of cutting are permissible. For this purpose only two instrumentalities are available, namely, the saw and the shear, either of which may be used on hot or cold material. Shears are of three general types; namely, the alligator, used only for cutting light weight material; the guillotine, which is employed generally for all classes of work; and the flying shear, designed to cut billets or bars while they are in motion. The power employed to operate the shears is hydraulic for the heavier materials, such as slabs and large blooms, while steam and electric power are used for all other work.

SECTION III.

SOME GENERAL FEATURES PERTAINING TO OPERATION OF THE ROLLING MILL.

The Mill Force: Of equal importance with the equipment of a mill, are the men who operate it and the organization and system back of them. Under the general superintendent of the steel plant there may be a number of rolling mill superintendents, each of whom will have charge of a group of mills turning out similar products. As his assistants, the mill superintendent selects foremen, each of whom are responsible for the successful operation of one or two of the mills. Below the foreman, the mill is divided into departments, with a man at the head of each, who is charged with the performance of a certain part of the work. Thus, there is the heater who has the heating of the material to look after; the roller, who superintends the actual rolling process; the engineer who tends the engine, or an electrician, if motors are used for running the mill; and the shearmen, whose duty is to see that the product is properly cut. Besides these, other departments, such as the machine and the electric shop, the inspection and shipping departments, play important parts in the mill operation, though they do not come under the direct authority of the mill superintendent. When it is remembered that the failure of any one of these may close down the whole mill, the importance of system and of the personnel of the organization is more fully appreciated.

Duties of the Roller: So far as the product of a given mill is concerned, it would appear that the roller and roll designer are the chief figures. Co-operation between these two men is essential, for in a measure their interests are identical; the roll designer decides how the work is to be done, and the roller sees that it is done properly. The latter will, therefore, concentrate his attention upon the product, and with caliper, gauge, or templet will take frequent measurements to make certain the material is being rolled true to the dimensions specified. He will keep a sharp look-out for underfills, overfills, fins, guide marks, collar marks, laps and any other rolling defects, and make the necessary adjustments to correct them.

Fins: It is the intention to discuss the defects of materials in connection with the rolling of each particular class of product, but in all rolling where grooved rolls are used, the occurrence of fins is so liable to happen that it is well to consider them here, more especially since there will be occasion to use the term frequently. Fins are formed when the section is too large for the pass it is entering, or whenever, in designing the pass, proper allowance has not been made for the spread of the material, thus causing the metal to flow out between the flat bodies of the rolls on each side of the groove. If this fin is thin and wide it will be folded over without welding and form a **lap**, when the piece, after turning, has been sent through

the next pass. Besides, fins may be dangerous, for if the rolls are very close together any spreading of material between them is likely to break them.

The Different Passes and Stands in mills that roll finished shapes are given class names. Thus the first rolls the piece enters in the mill are used mainly to reduce the size of the bloom or billet, and the piece generally leaves them in the same shape it entered. These passes are called the **roughing rolls** and the stand or stands is spoken of as the rougher, or roughers. If the succeeding stand merely carries this reduction further, it is called the **pony** rougher. The stands and passes in which the actual shaping of the piece is done are called the **strands,** usually numbered 1, 2, etc. The pass next to the last is called the **planisher,** but since in roll designing this pass may be looked upon as the first pass leading back from the finished section to the bloom, some designers call this pass the **leader.** The last pass is always called the **finishing.**

Factors Affecting the Rolling Operation: In the rolling of steel there are five factors to be considered, namely, the temperature of the steel during the rolling, the chemical composition of the metal, the speed at which the rolls are revolved, the draught in each pass, and the diameter of the rolls. Furthermore, these factors should be considered from the three different standpoints of power, or energy, required to deform the steel; their effect upon the rolling properties of the metal, that is, the way it will spread, bend and flow in the rolls; and their effect on the quality of the finished product. All these matters have not been fully investigated, and our knowledge concerning them is somewhat meager, but in order to invite attention to these subjects, a brief summary of what is known about these factors is appended.

Effects of Temperature: The influence which the working of steel at different temperatures may have upon the quality and properties of the product has already been discussed under the caption of Hot and Cold Working, (Chap. II, Sect. 1.). Relative to the power or energy requirements and the rolling properties of the metal, it is to be observed that the higher the temperature is raised the more plastic the steel becomes. Thus, while, a .10 per cent. carbon steel, for example, will give a tensile strength of about 50000 pounds at atmospheric temperatures, at 600°C it will break under a pull of 20000 to 25000 pounds per square inch, at 700°C under a pull of about 11000 pounds, and at 800° C. under a pull of about 6000 pounds. Between 800° C. and 900° C. a distinct discontinuity in the tensile strength occurs, with the result that at 900° C. the tensile strength will suddenly increase to nearly 9000 pounds. From this point the strength decreases with rising temperature, being about 6500 pounds at 1000° C., about 4600 pounds at 1100° C., about 3000 at 1200° C., and approaching zero at about

1480° C., the point of incipient fusion. From these facts it would appear that the higher the temperature of the steel the easier will it be deformed. But there are other features that tend to keep both the initial and final working temperatures within certain well defined limits. Since steel assumes a semi-fluid state at temperatures somewhat below its fusion point, heating to within less than 200° C. of this point exposes it to the danger of overheating or so-called "burning." For soft steels the initial temperature should not exceed 1300° C. (2372° F.), and for high carbon steels (1.00% to 1.20% carbon), this temperature should not exceed 1100° C. (2012° F.). In order to secure the greatest refinement of grain, either the initial temperature or the speed of rolling should be adjusted so that the finishing temperature of the rolling will be above, but as near the critical range of the steel as possible.

The Effect of Chemical Composition need be considered here only from the standpoint of rolling properties and energy required for rolling. As to the energy required, experiments have shown that slightly more work is required to roll a steel containing 1.00 per cent. carbon than for steels containing only .10 per cent. carbon. Whether this difference was due entirely to the lower temperature at which the higher carbon steel was rolled or also partly to the higher content of carbon could not be determined. In the hope that it would help to solve this question, an experiment was performed with the object of comparing the tensile strength of high carbon and low carbon steels at rolling temperatures. For this purpose three steels having a carbon content of .10 per cent., .22 per cent. and 1.10 per cent., but otherwise of approximately the same composition, were selected. The results from pulling the first have already been given. The mechanical properties of the other two were compared at 900° C. only. The average results obtained from pulling ten pieces of each under similar conditions at the initial temperature of 900° C. are as follows:

Carbon Content	Tensile Strength	Elongation in 8″	Reduction of Area
.22%	13,500 lbs.	110%	94%
1.10%	18,800 lbs.	58%	83%

These results would indicate that the higher carbon steel is somewhat less plastic at rolling temperatures than the lower carbon steel. Therefore, it would require more energy for rolling, and would not spread or elongate as readily as the steel of lower carbon content. As to the effect of the other elements in plain steel, phosphorus may produce effects similar to those of carbon, sulphur tends to produce red shortness, while manganese tends to offset the effects of sulphur and oxygen and improve the rolling properties. Open hearth steel, which is low in its phosphorus content, tends to spread more in the rolls than does Bessemer steel, which is higher in phosphorus. The rolling properties are still more strongly affected by certain alloying elements, such as nickel and chromium. The difference in rolling properties produced by difference in chemical composition may not

be noticeable in the rolling of the simpler sections, but may cause much trouble in the rolling of complicated sections with wide thin flanges or legs. Thus, in one instance of such a complicated section, it was found that while the section rolled perfectly with one heat of steel, it was imperfectly formed when rolled from another heat in which the carbon content was ten points, the manganese fifteen points, and the sulphur two points higher, although in both cases the same set of rolls was used and adjusted in the same way.

The Effect of Speed: The speed of rolling is the factor which has received the least attention from the viewpoint of its effect upon the material. It is the consensus of opinion among steel workers, however, that the speed of rolling undoubtedly has an influence upon the quality of the product. It is evident that the faster a piece of steel is deformed the less time the molecules have in which to adapt themselves to the deformation and the greater their resistance to the deformation. Consequently the stretching effect of the rolling, as previously explained, increases in undue proportion to the compression. If the speed of the rolls were increased sufficiently they would then have a greater tendency to slip on the piece, and the stretching effect would tend to become a tearing effect. However, it is not speed alone that produces this effect but draught and speed together.

Draught: Draught is the difference in sectional area between one pass and the next succeeding one, and is usually expressed in per cent. While there are cases where as high as a 50-per cent. reduction occurs, and one case in which a 70-per cent. reduction is made in a single pass, the draught will seldom exceed 36 per cent. These heavy draughts take place in the roughers, where most of the reduction occurs. In the strands the reduction will be as evenly distributed as possible, and will sometimes be as low as 10 per cent. If the leader is used as a planishing pass very little reduction is effected there either, while very little reduction, with a few exceptions, ever occurs in the finishing pass. This pass being intended to give an exact finish to gauge and to true up the piece, it is important that very little work be done in it in order that it may be subjected to as little wear as possible. Since a piece must be finished before it has lost its heat and has cooled below the rolling temperature, which cooling is very rapid in the case of small sections, the rolls must be run at a speed that will carry the piece through the rolling before it has become too cold. The number of passes and the size of the piece to start with control the draught. Aside from these features the desire to increase output acts as an incentive to increase both the speed and the draught to the limit the material will stand. There are many considerations, however, that operate to hold down both speed and draught below that which will do injury to the steel. One of these is the additional power required for very rapid reduction; another is the severe strain on the rolls and other machinery when the piece enters the rolls at high speed and with large draught. In mills composed of several stands, especially in the case of the continuous mill, the speed of all preceding stands is determined

by the speed of the finishing stand. In hand mills, the speed is restricted to the highest velocity, about six hundred feet per minute, at which the catchers can grasp the piece with the tongs. The magnitude of the draught is restricted by the limiting angle at which the rolls will "bite" the piece on entering. This angle is found, by experience, to be about 30°.

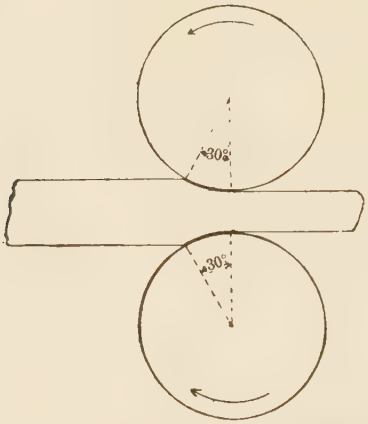


Fig. 121. The Limiting Angle of Rolling.

Above this angle the resultants of the forces of compression have receded so far from a parallel to the line joining the centers of the rolls that they exert a push on the piece, and the resultant of the forces of elongation is so nearly vertical that the horizontally inclined component due to friction only is not sufficient to balance this backward push and drag the material between the rolls. In order to increase this limit, a series of horizontal and well rounded grooves, called **ragging,** are often cut in the surface of the roll, giving it the appearance of a half formed cog wheel. Since these grooves leave ridges in the material, they can be resorted to only in blooming mills, billet mills, or roughing stands. Even then the grooves must be cut with considerable care in order to prevent these ridges being folded over into laps in succeeding passes and rolled into the material, to appear as seams in the finished product.

The Effect of Diameter of Rolls: From a study of Fig. 121 it will be seen that the larger the roll diameters are the greater will be the draught that may be taken without exceeding the limiting angle of rolling. For the same draft, however, a large roll gives a greater roll surface area in contact

with the metal than a small one and therefore requires more pressure to force it into the metal, thus putting a greater tension on the housings and requiring more energy to drive it. The large roll gives an affect more like that of pressing than the small roll, and, with the draft and speed properly regulated, the effects of the rolling can be made less superficial with the large roll. The large roll tends to cause the metal to spread more than the small roll. Hence, the size of the rolls is a factor to be considered in designing rolls for flats and other products in which the spread of the metal may affect the dimensions of the finished article.

CHAPTER IV.

PREPARATION OF THE STEEL FOR ROLLING.

SECTION I.

INGOTS AND THEIR DEFECTS.

Preparation of Ingots: In order that the large bodies of metal refined at one time by the various methods of steel making may be obtained in a convenient shape for rolling, it is necessary that these large bodies be divided into smaller ones, called ingots, of a uniform shape and size. These conditions are obtained by pouring the metal while it is still molten into moulds of the desired dimensions, where it may be allowed to solidify in part or in whole before the mould is removed. Before rolling begins, however, the ingot must have been allowed to solidify throughout, and the whole mass should be of uniform temperature. But in cooling naturally, these conditions are not fulfilled, because the outside of the ingot, being the part from which the heat is removed the most rapidly, is the first to solidify. With this fact in mind, it is easily understood how, in any case of natural cooling, the interior is the last to drop to any given temperature. In fact, the moulds are stripped from many ingots while the central portion is yet in the liquid state. This fact was early recognized by steel workers. So it was originally the custom to strip the ingots as soon as possible and place them in a tightly covered hole or pit in the ground, where the heat from the interior of the ingot was slowly conveyed to the outside by conduction, and sufficed not only to heat up the colder exterior part of the ingot but also to supply heat to the pit, which, with careful manipulaton, was sufficient to maintain a rolling temperature. This process was called **soaking,** hence the name **soaking pit.** In order to bring the soaking under better control and make it adaptable to varying conditions, means for supplying additional heat was introduced, so that the modern soaking pit is in reality a kind of heating furnace, a detailed description of which will be given later.

Ingot Defects: A prerequisite to faultlessly finished material is perfect ingots, and by a perfect ingot is meant one free from all cavities or openings and made up of material that is homogeneous throughout. Unfortunately, the natural laws that govern the solidification of the liquid metal operate against both these requirements, and develop the well known natural defects in ingots called piping, blow holes, segregation and crystallization. Added to these are other defects, both incidental and accidental, such as checking, scabs, and slag inclusions. A brief discussion of these defects follows; but an understanding of their causes requires a study of the laws that control the cooling of ingots.

The Nature of the Cooling of an Ingot: The ingot moulds in common use are tall box-like shapes made of cast iron; they are open at both ends, one of which is a little smaller than the other to give the mould a little taper; and they have a square or rectangular section slightly rounded at the corners. In use, one end of the mould, usually the larger, is closed by the **stool** on which the mould stands in an upright position. As soon as the molten steel is poured into this mould, the metal next to the mould and stool is chilled by contact with the cold surfaces and solidifies on the bottom and sides to form what is called the **skin** of the ingot. As more and more heat is absorbed by the mould, this skin grows in thickness, but due to the increase in the temperature of the mould and the insulating effect of the skin, itself, it grows at a rapidly reduced rate, until the process becomes so slow that it can be considered as a normal cooling. The cooling then takes place by a dissipation of the heat through this skin along lines perpendicular to the surface of the solidified shell, which acts as the conductor, with the result that this shell gradually grows in thickness, the growth progressing toward the center until all the metal is in the solid state. The laws of freezing which the metal obeys, combined with this manner of freezing, gives rise to the natural defects enumerated above.

Pipes: One of the most noticeable effects of the freezing is the production of a more or less cone-shaped cavity at the top of the ingot, known as the **pipe.** Pipes are the result of the contraction of the metal on solidifying in the manner just described. This contraction amounts to about two-hundredths of the linear dimensions of the ingot, and if the manner of cooling did not set in play forces which oppose the contraction, no pipes would form, and a perfect ingot would measure one-fiftieth smaller than the mould in all its dimensions. In ordinary ingots much of this difference in volume is represented by the pipe. Since the skin and the more slowly formed walls built up by the cooling are rigid, the void left by contraction is filled by the metal in the central portion that still remains fluid, the force of gravity directing the flow downward at all times. After solidification of the metal is complete, further contraction on cooling tends to open this pipe still farther towards the bottom, because the exterior, being the colder, is the more rigid and is capable of stretching or tearing the more plastic interior. The greater portion of the surface of this cavity is likely to become more or less oxidized, and, since the oxidized portion is not welded up in the rolling, the pipe will appear in the smallest rod or wire into which this part of the ingot may be rolled. Aside from injuring material, pipes are liable to cause accidents in rolling, so the steel maker is very anxious to get rid of them as early as possible.

Methods of Reducing Waste Due to the Pipe: Obviously, the only way of avoiding this pipe is by discarding the portion of the ingot affected. Various schemes for reducing the waste due to this cause have been and are being tried, and some of them are fairly successful, among which the

Fig. 122. Split Ingots Showing Various Forms and Degrees of Pipe.

FIG. 122—Continued

most promising seems to be the so-called **hot top mould.** As explained in connection with the open hearth process, in one form of these moulds the ingot is cast with the smaller end down, while the larger end is surmounted with a short mould which is lined with refractory and non-conducting material, such as clay. This lining reduces the size of the top section and keeps the top of the ingot in the molten state until the ingot proper has solidified. Thus, the pipe is brought up into the cope, or sink head, which is of much smaller section than the ingot, and the waste due to the cropping is decreased accordingly. This ingot is stripped by first removing the insulated top section, gripping the sink head with tongs and then lifting the ingot out of the mould. In a patented form of this mould, known as the Gathman mould, a similar effect is produced by decreasing the thickness of the mould at the top. Since the heavy part of the mould causes a more rapid cooling than the thin portion, the metal at the top is the last to freeze.

Blow Holes: In the molten state iron, or steel, is capable of dissolving large volumes of gases, such as oxygen, hydrogen, nitrogen and carbon-monoxide, this solvent power changing with the temperature and the composition of the slag. The iron probably unites with all the oxygen immediately after it is dissolved, hence it is retained by the metal in the solid state if chemical means are not employed to remove it. In case of the other gases, however, no such stable combination takes place, and they are largely thrown out of solution just previous to the time when solidification of the metal occurs. As the metal is in a more or less plastic condition at this time, the last gases thus liberated may not be able to escape from the body of the metal, in which case they collect in bubbles, as a gas will in making its way out of any fluid. Each bubble then forms a small cavity in the metal, which is known as a **blow hole.** These holes vary in size from those visible through a microscope to large pockets, the dimensions of which can be measured in inches. The smallest ones are apt to occur just below the skin of the ingot where the rapidly cooling metal gave the tiny bubbles of evolved gases time neither to escape nor to collect in larger bodies. Here the gases, unable to escape upward on account of the very viscous nature of the metal, form tube-like cavities that extend at right angles to the skin, or wall, of the ingot and toward the center. In the rolling of the steel, the blow holes are closed up and welded together, provided their surfaces have not been oxidized. In case these walls have been oxidized, they will not weld and will produce defects in the finished articles. Blow holes near the center of the piece, known as deep seated holes, are less liable to oxidation, hence are the least harmful. But the small blow holes beneath the skin of the ingot are liable to be exposed to the air, or be filled with liquid oxide of iron, in which case they produce **seams** in the finished articles. Blow holes are an ever present menace. But corrective may be employed successfully, and they are seldom a source of serious damage in steel that has been properly

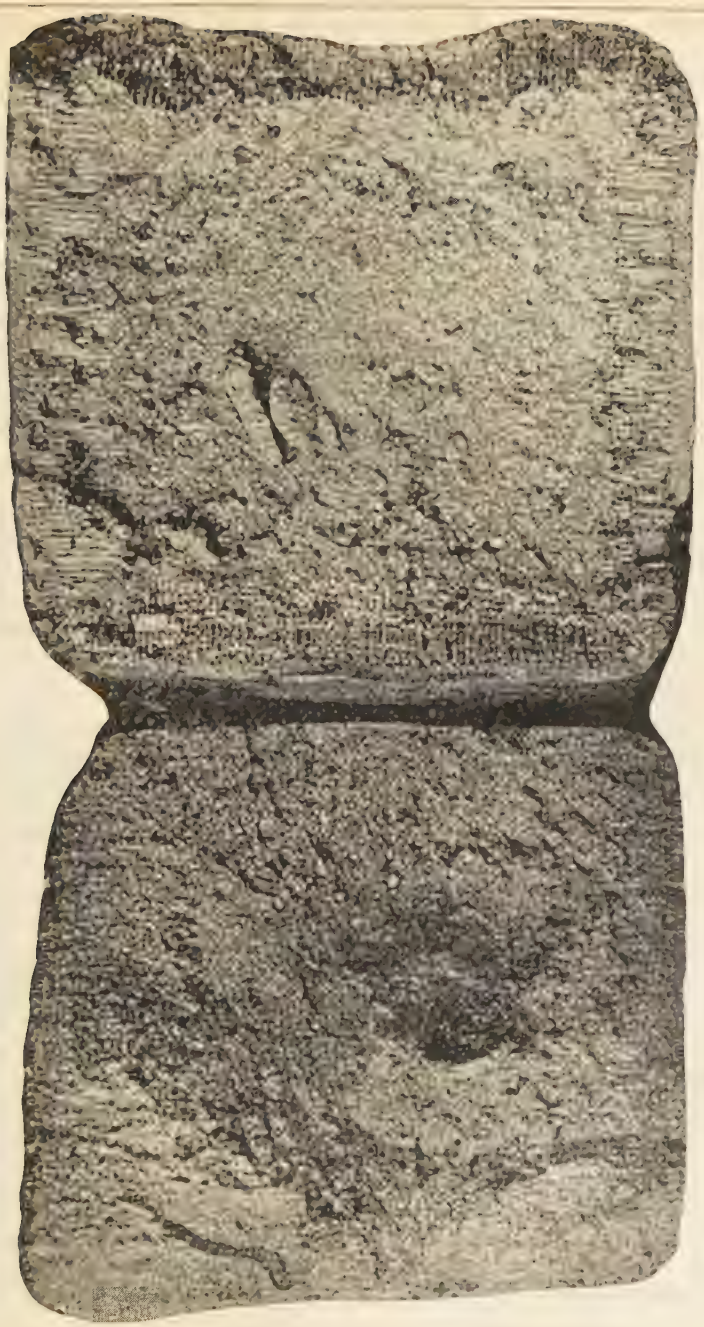


Fig. 123. Transverse Sections of Ingots Showing Blow Holes

worked in the process of manufacture and thoroughly deoxidized at the time of recarburizing. In this respect the use of aluminum in the mould at time of casting has been found to be very effective. Blow holes have the effect of reducing the size of the pipe, and on this account are to be desired if they are deep seated. Various attempts to overcome both blow holes and pipes mechanically by means of subjecting the metal to compression while in the molten state have been tried, but the expense of operating these appliances more than outweighs the good derived, especially since the steel discarded on account of pipe is available for use as scrap in the open hearth.

Crystallization, as already indicated, is the property possessed by iron, in common with many other substances, of forming crystals on solidifying. The size of the crystals depends on the composition of the steel and the rate of cooling; in general, the slower the cooling the larger the crystals will be. It is plain that the temperature at casting and the size and shape of the ingot and mould control the rate of cooling. If the crystals are large, the force of cohesion among the crystals is decreased at high temperatures, while at lower temperatures they offer less resistance to slip than small crystals. The effect of unduly large crystals is to make ingots liable to tear in rolling. This condition is sometimes called **ingotism.** The deformation and consequent refinement of the crystals due to rolling, hammering or pressing, prevent their effect showing up in finished product that has been properly worked.

Segregation: Steel is a mixture of various compounds and elements, and although some of these are to be looked upon as impurities because of their detrimental effects, others are necessary to impart the properties most desired in the product. While the steel is in the molten state, these solid ingredients, like the gases just mentioned, are held in solution by the iron, a power which it does not possess to the same degree at temperatures below its freezing point. Some of these ingredients freeze at a lower temperature than the iron. Furthermore, the solution, following the laws of selective freezing, undergoes a series of changes and recombinations with the formation of various eutectic solutions, which increase the number of substances that solidify normally at much lower temperatures than pure iron. With such an aggregate, it is easy to see how the process of solidification results in an isolation of the ingredients. Those substances having the highest melting, or freezing points, of course, are the first to crystallize. This separation, then, has the effect of concentrating the solution of the substances having the lower freezing points in the mother liquor. This process continues until the mother liquor is made up only of that substance that has the lowest freezing point, when it, too, will freeze, forming in the ingot a solid mass very different in composition from the metal that crystallized out at the beginning. Under such conditions, it is to be expected that the substances with the low melting points would be found in one spot or locality in the ingot and that

this spot would be located near the top and center of the ingot, that is, at the bottom of the pipe, where the metal was the last to freeze; and to some extent, that is what actually does occur, as shown by Fig. 124, so that this central position of the ingot is spoken of as the **line of segregation.** That the condition is not even more pronounced is due to the closing in, or entrapping, of the small pockets of the mother liquor during the freezing, and to the high viscosity of the fluid. Like the pipe and the blow hole, segregation cannot be overcome, but by rapid cooling and the use of aluminum to quiet the metal it may be lessened somewhat. In conclusion it should be remarked that this is one of the fundamental reasons why a range in chemical and physical specifications is imperative, at least from the manufacturer's point of view.

Checking and Scabs: If the surface of a mould is very rough, or contains cavities, so that resistance is offered to the natural contraction of the steel, transverse cracks in the skin of the ingot may result. However, in spite of all precautions that may be taken, cracks in ingots will occur, and a study of this matter indicates that this defect is more liable to occur in certain grades of steel than in others, and particularly in those steels in which the carbon content is between .17 per cent. and .24 per cent. These cracks become oxidized, and subsequently produce a seamy product. Scabby material is often caused by improper pouring. If care is not taken to prevent it, the metal may be splashed against the side of the cold mould during the pouring. These splashes tend to stick to the mould, and, becoming oxidized on the surface, will then appear as scabs on the ingot after it is stripped. These defects very often show up after rolling in the form of seams and slivers; in plates they will form serious surface defects. Such defects are entirely avoided by bottom casting the ingots. A cracked mould that must be forcibly drawn by the stripper may produce similar defects.

Non-metallic Inclusions: Various explanations are offered to account for the particles of slag and other foreign substances held within steel. Slag inclusions may be due to an improperly finished bath, or in case the furnace practice has been good, they may be caused by slag being stirred into the steel and mechanically held by it while the heat is being poured. Other foreign substances may be due to dirt in the ladle or moulds, or they may be the result of slag forming reactions that occur during the deoxidation of the metal in the ladle or moulds. The latter cause would seem most conducive to the formation of the minute slag-like particles that occur so frequently in nearly all steels. These particles, if given the opportunity, will rise to the top of the metal in the ladle, but for lack of time small particles do not always do so. Such particles remaining in steel after it has been teemed have little opportunity to rise, because the chilling of the steel by the mould is so rapid, and they are, therefore, entrapped. Hence, deoxidation in the mould should be controlled by good judgment and avoided when possible. Large slag inclusions are an original source of blisters in finished products.

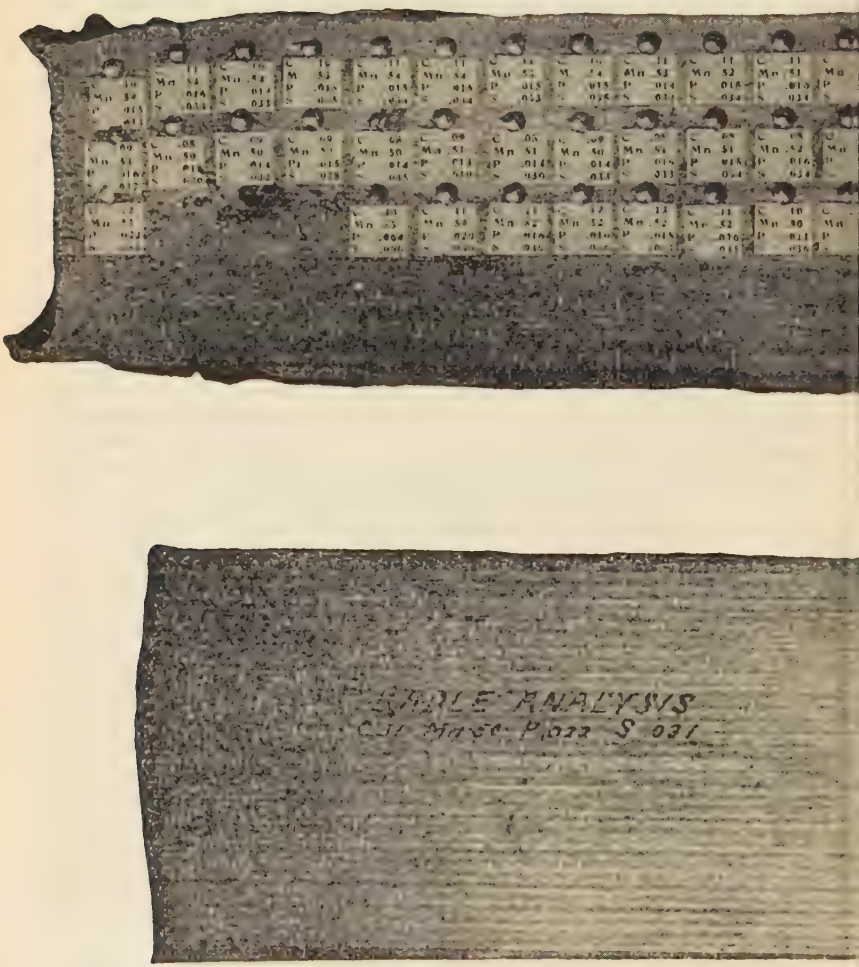
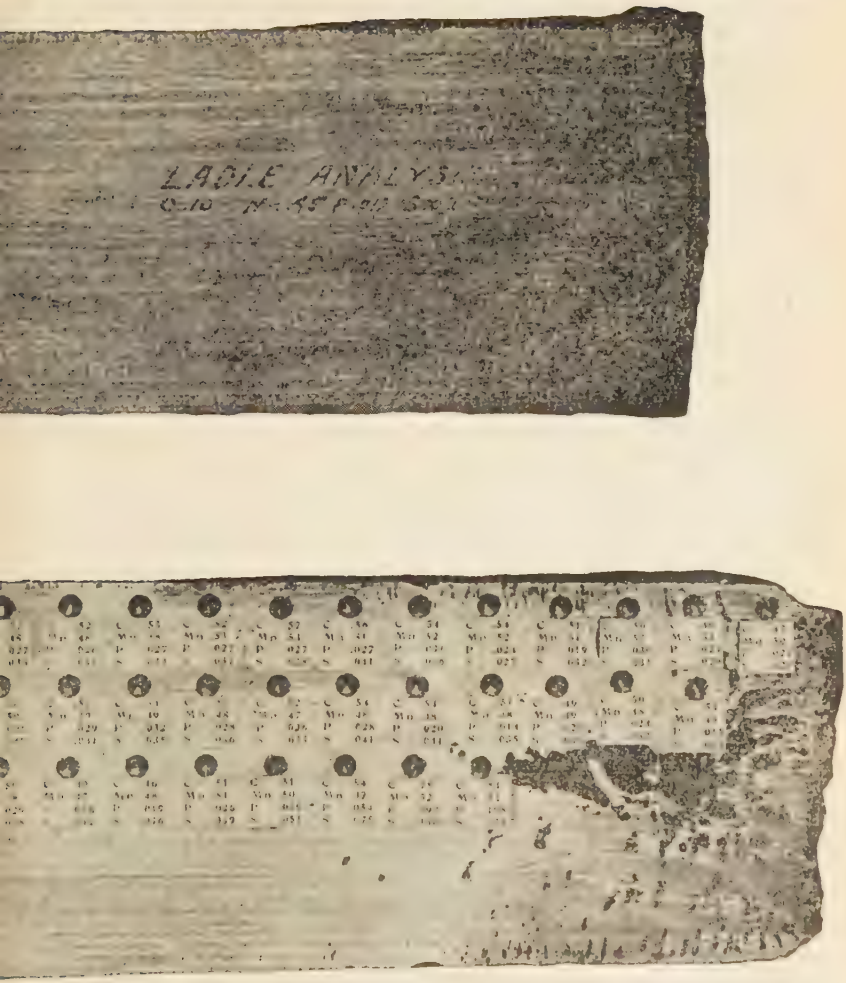


Fig. 124. Split Ingots Showing Analyses of



Metal in the Region of Greatest Segregation.

Size and Shape of Ingots: With regard to the size of ingots a number of factors operate to control both the size of the section and the length. First of these is pouring cost. It is obvious that the cost of teeming a 50-ton heat into two-ton ingots will be much greater than if the same heat is cast into four-ton ingots due to increased number of moulds required, the increase in scrap produced, and the longer time consumed in stripping and charging into the soaking pits, etc. The cost of rolling may be increased, also, for a long ingot may be rolled with the same number of passes as a short one of the same section. The product desired, also, is a factor in determining the size and the shape of the ingot. In plate mills, for instance, which operate independently of slabbing mills, the size of the plate to be rolled determines the size of the slab ingot. The blooming and slabbing mills and their equipment, once installed, fix a maximum limit to the size of the ingot both as to section and length. As to their shape, ingots may be of any convenient form, though for rolling they are usually square or rectangular in section with rounded corners. These forms are easiest on the steel, as the flat sides offer the least resistance to contraction on cooling, and the rounded corners prevent rapid cooling along the edges, which cooling would result in cracks from subsequent contraction on cooling. For forging large rounds, a round ingot with a corrugated surface is used. The corrugations permit expansion and contraction of the ingot without the danger of developing cracks that are liable to occur in the surface and interior of ingots cast in a perfectly cylindrical mould. The taper on ingots is to facilitate the stripping. To express the size of a rectangular ingot the dimensions of its largest section are always given, unless otherwise specified. Thus, a 23½ inch ingot means it is 23½ inches square at the butt; an 18½ x 21½ inch ingot means it is rectangular in section and 18½ x 21½ inches at the butt.

SECTION II.

THE CONSTRUCTION OF THE SOAKING PIT.

General Features of the Soaking Pit: The soaking pit of modern construction is so built that it can be used either as an old time pit or as a heating furnace. Briefly, soaking pits are deep chambers, or underground furnaces of square or rectangular sections, heated by the regenerative principle and opening at the top. As to size, they are built large enough to contain four, six, or eight blooming mill ingots per hole, in an upright position. The older furnaces contain four ingots per hole, while the capacity of the most recent ones is eight ingots. The increase in size is due mainly to the economy in fuel which is obtained by the use of large pits. While the details of pit construction may vary somewhat at different works, yet the form and principle of all are alike. Therefore, it is sufficient to study but one, which may serve as an example of all. For this purpose, a six ingot furnace at Duquesne will be described somewhat in detail.

Arrangement of the Pits: For heating the ingots for the two blooming mills at these works, the 38-inch and 40-inch mills, there are 11 rows of pits, or to be more exact, 11 furnaces of 4 holes each. The holes are numbered 1 to 44, inclusive. No. 1 to No. 20 and No. 37 to No. 40 serve the 38-inch mill; the other 16, No. 21 to No. 36, inclusive, serve the 40-inch mill. In case a furnace for the 40-inch mill is off for repairs No. 5 furnace, containing holes 17, 18, 19 and 20, may be substituted. The first nine furnaces are built to contain six 22″ x 22″ ingots per hole, but numbers 10 and 11 are constructed to hold eight ingots per pit. This gives a pit capacity for the 40-inch mill of 96 ingots, and for the 38-inch mill, 184 ingots. The furnaces, with the exception of No. 1, are built in groups of two each. From center to center of each two adjacent furnaces, the distance is thirty-three feet.

Equipment for Handling Ingots: Spanning these soaking pit furnaces are electric traveling cranes, two of which are over furnaces No. 10 and No. 11, and four are over No. 1 to No. 9, inclusive. These cranes are Morgan 6-ton machines, and are equipped with Westinghouse motors as follows: 50 h. p. on the bridge, 50 h. p. on the hoist, 10 h. p. on the trolley, and 5 h. p. on the tongs. The main hoist is operated by a gear hoist and shafting rack. The tongs are connected up with a drum on a lifting arm, giving a vertical movement of about nine and one-fourth feet. The tongs are actuated by means of a curved groove in the main hoist so that their distance apart may be varied. The tongs are equipped with four-inch bits, giving a distance between the two bits, when in the closed or lowered position, of sixteen inches and when in the raised or open position a distance of nineteen and five-eighths inches. Thus the largest ingot that can be gripped is one about eighteen inches at the top. When larger ingots, such as the 22″ x 22″ size, are to be handled it is necessary to remove one bit.

Construction of the Pits: In detail the construction of a six-ingot soaking pit furnace is as follows: Each furnace or pit contains four rectangular holes, eight feet long, five feet three inches wide and eight feet seven inches deep. These holes are built side by side in the furnace, and are separated only by firebrick walls. Each hole has two air regenerators, one on each side, so that in connection with each furnace there are eight regenerators. The holes are closed by firebrick covers, each cover being supported on four wheels which roll on cast steel rails lying on the division wall between the pits and fastened at their ends to the I-beams supporting the platform about the pits. The walls enclosing the checkers and those supporting the pit proper rest on a concrete foundation twelve inches thick. These walls are built of firebrick, faced on the outside with river brick. The outside walls are about eighteen feet high, and the river brick wall directly under the pit is about eight feet high. The top of this river brick wall is protected by cast iron coping plates. Placed vertically on these coping plates and extending up into the firebrick bridgewall are cast iron end plates. On the coping plates rest also the

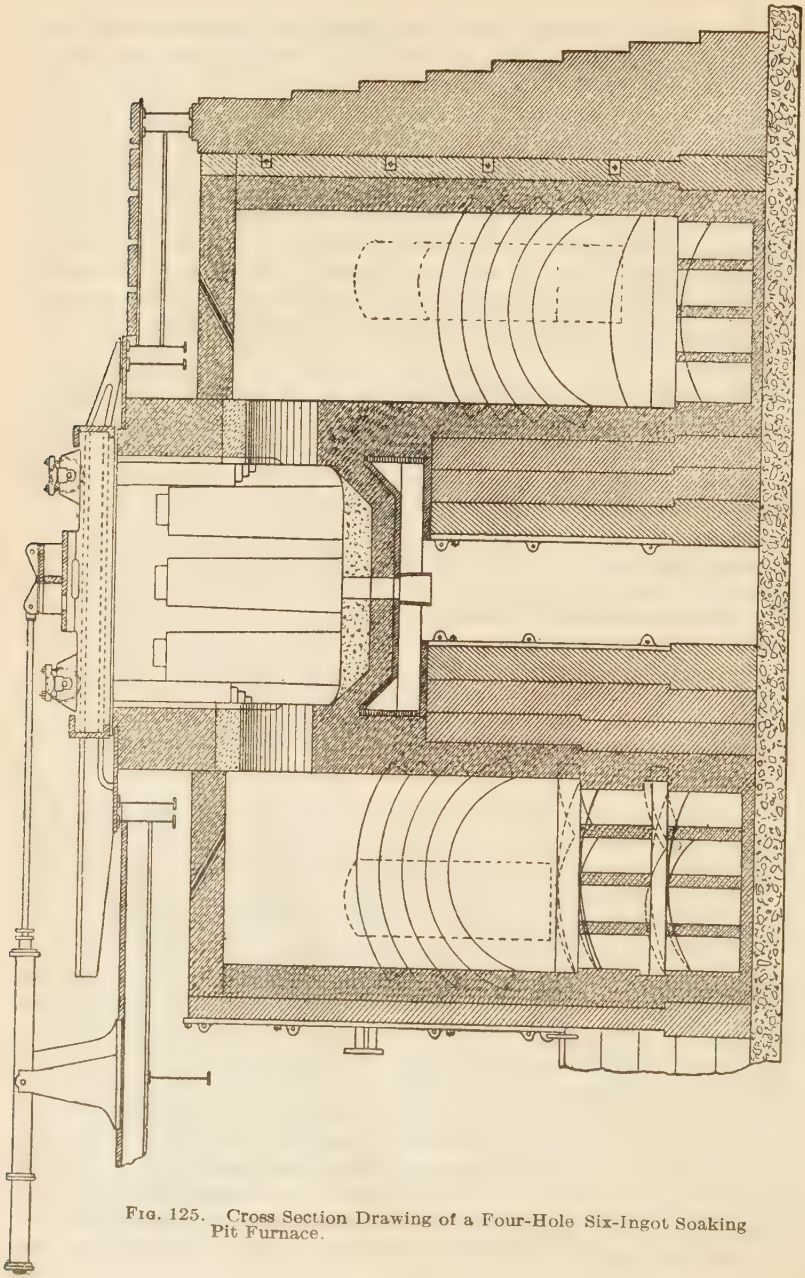


Fig. 125. Cross Section Drawing of a Four-Hole Six-Ingot Soaking Pit Furnace.

steel I-beams supporting the cast iron pans which form the bottom of the pits. A pan is made in two sections with a semi-circular hole on the inside edge of each section, so that when they are fitted together there will be a circular opening about ten inches in diameter through which the cinder can be removed from the pit. Each section rests on three ten-inch I-beams. About one foot on each end of the pan is flared upward at an angle of 45°. There are five cooling boxes resting on the I-beams, three inside, or intermediate cooling boxes, and two end ones. The inside cooling boxes are in the division walls between the pits, and the end ones are in the end walls of the two outside pits. Each of these boxes rests on two I-beams. The boxes are hollow, being open on the bottom, and the lower half of the end of the bottom is cut off at an angle of about 45°. Thus, these cooling boxes and pans form with the end plates a triangular space through which the air circulates and forms the air cooling system for the bridgewall. On the top of the cooling boxes and near each end, there is a four-inch hole, and when the walls between the pits are built up, this opening is extended up to the surface so that a circulation of air is maintained through it. The boxes are cast iron, one inch thick, eight feet nine inches long, twenty-eight inches high and are fourteen inches wide inside at the bottom and four and three-fourths inches inside at the top. The pans are lined with nine inches of firebrick set in firebrick mortar. The cinder hole is built up of nine-inch side-arch brick. The pit, then, to above the slag line, is lined with chrome brick, as these are the only bricks that are not fluxed by the slag formed. Next to the coolers, however, there is one four and one-half-inch course of firebrick, laid in fireclay, but on these there is a four-inch course of chrome bricks, laid dry, and at the front and back of the pits, at the bridgewall, this chrome brick lining is nine inches thick. There are, in all, seven courses of chrome bricks, which bring the wall even with the top of the cooling box. Above this level, the walls are built entirely of firebrick. The side of the bridgewall next to the checker chambers is capped with heavy firebrick tiles ($13\frac{1}{2}$ x 6 x $2\frac{1}{2}$″) giving a width to the firebridge of twenty-two and one-half inches. The chrome bricks are heavily coated with silica slurry, which affords an added protection. The use of this slurry is especially important on the front and back, for the bridgewall is the weakest part of the furnace, because it is subject to the intense heat of the products of combustion leaving the pit, and, therefore, has a tendency to crack and spall. The firebrick part of the walls inside of the pit are coated with a slurry of fireclay. This coating fills up the cracks and forms a glaze which protects the bricks.

The Air Regenerators are about six feet square in horizontal section and seventeen feet four inches deep. The sewer which conducts the air from the air valve to the two chambers on the same side and farthest from the stack is beneath the air sewer for the two pits nearest the stack. Thus, the regenerator chambers and, hence, the pits are fired in pairs. The bottom

sewer is two feet seven inches high and the arch is nine inches thick. Therefore, the regenerator chambers for the two pits, on each side, nearest the stack are three feet four inches less in height than the back chambers. Between the two regenerators on the same air flue, starting at a height of about five feet above the bottom of the chambers, there is an eighteen-inch firebrick wall separating the two adjacent chambers. The two pairs of regenerators on the different air sewers are entirely separated from each other. The bottoms of the chambers are separated into four spaces (fourteen and one-half inches wide) by firebrick rider walls. These walls extend back into the air sewer to the air valve and provide for the even distribution of the air. On these rider walls there is one course of firebrick tiles on which the checkers rest. The rider walls are three feet seven inches high in the two pairs of regenerators farthest from the stack and two feet four inches in the other two pairs, thus making the height of the first mentioned checkers nine feet six and one-half inches. In the two pairs of chambers farthest from the stack, the checkers extend up to within thirty-one inches of the bridgewall and in the other two pairs to within eighteen inches. The top row of checker bricks are laid so that the openings are in the same direction that the air must take in entering the pit. The roof of the regenerator chamber is arched, being built of firebrick thirteen and one-half inches thick, but the arch over the bridgewall, for a distance of twenty-seven inches, is of silica brick, nine inches thick and laid in silica slurry, on top of which is a thirteen and one-half-inch firebrick arch. Silica brick is used in this construction because it is very refractory and can withstand a heavy load when highly heated. The whole furnace is securely tied together by cast iron corner binders, tie rods, and buckstays. Each of the four outside corners of the furnace has a corner binder fifteen feet ten and one-half inches high, and the four corners directly under the pits have binders eight feet one inch high. These binders have a twelve-inch flange, two inches thick, provided with lugs for the tie rods. The binders are connected by two-inch tie rods. Along the two outside walls of the regenerators there is a structural steel buckstay, the ends of which are connected across the furnace end by two-inch tie rods.

The Pit Covers consist of four iron castings which are bolted together and are held rigid at the center by a cast iron separator. Inclosed in this frame is a firebrick arch. As already stated, to these castings are fastened the wheels on which the covers roll. To each separator is fastened a steel piston rod connected to the piston head in a hydraulic cylinder. These cylinders furnish the means by which the covers are moved. In some plants the covers are moved by lowering the tongs into a special box in the separator casting and then moving the crane in the direction desired. The hydraulic cylinders operate under a water pressure of 500 lbs. per square inch. They rest on cast iron stands fastened to the floor beams, and the bearings for the cylinders are placed about the center of the cylinders, thus making them free to rotate about this point. This con-

struction is made necessary, because, as the furnace becomes old, the dividing walls between the pits sink and the rails bend. Therefore, the connection of the piston rod and the separator has a constantly varying elevation due to the different elevation of the rails, and it is necessary to have the cylinders on a rocker so that they may follow this motion and constantly adjust themselves in line with the piston. The extreme stroke of the cover piston is nine feet nine inches. In order to make the covers fit nicely the tops of the pits are surrounded by floor plates of cast iron.

Fuel and Air Valves, etc.: These pits were built to use natural gas for fuel, but this fuel has been replaced by coke-oven gas. When natural gas was used for heating the pits, it was admitted through the roof of the regenerator chamber by means of two three-fourth-inch pipes twenty-one inches long. These pipes were placed at such an angle (about four and one-half inches of slope per foot) and distance from the pit that the flame did not play directly on the face of the ingot, and a reducing atmosphere could be maintained inside the pit. The pipes, or burners, were twenty-one inches apart and were fed from a one and one-fourth-inch pipe which in turn was connected up to a four-inch gas manifold supplying the gas to the four chambers on a particular side. For coke oven gas it was thought it would be necessary to modify this scheme of firing somewhat in order to make the conditions suit the difference in the heating properties of these gases, but trial runs indicate that satisfactory results are obtained if the coke oven gas is burned in the same manner as the natural gas. For reversing the direction of the air there are two thirty-inch Ahlen sliding valves, and for reversing the direction of the gas a three-way valve. Each set of valves consists of two cast iron bed plates, two cast iron sliding plates, two hydraulic cylinders, and two hoods. The distance from center to center of the hoods is five feet three and one-half inches. The bed plates are bolted together and the cylinders are bolted to them. Each of these bed plates has three openings connected to flues, of which the two outside ones lead to the regenerators and the center one to the stack. These flues are twenty-two inches wide, the division walls being nine inches thick and the wall between the two sets of valves twenty-two and one-half inches thick. As to the sliding plates they are also bolted together and the two are then connected directly to the piston of the hydraulic cylinder. The total length of the sliding plate is eleven feet one inch. Each plate has six openings, two pairs of which are used as air dampers, while the other two form, with the hood, a part of the flue to the stack. The hood rests on the sliding plate, and both the hood and the sliding plate are water cooled. The hydraulic cylinder has a stroke of two feet seven inches and a plunger diameter of six inches.

Stack-flues and Stack: The flues leading from the valve to the stack are three feet eleven inches high and twenty-two inches wide. In these flues are the stack dampers. These dampers are hand operated by means of a chain and a counter-weight. They slide in a guide frame made

in the form of a casting set in the brick work. The stacks are one hundred three feet eight inches high, and consist of a riveted steel shell and a lining of brick work. The plates of which the shell is made are one-fourth inch thick at the bottom of the stack and one-eighth inch at the top. The outside diameters of the shell at the top and bottom are respectively four feet six inches and five feet ten inches. The lining consists of a four and one-half inch course of firebrick.

The Course of the Gases Through the Pits: Of the two thirty-inch air valves, the one nearest to the pits is for the two front pits and the other for the two back pits. Thus, for the two front pits, the air enters the inside valve through the top sewer, goes through the two front regenerator chambers, the two front pits, down through the opposite checkers, through the top sewer, through the inside reversing valve, then past the right hand stack damper to the stack. For controlling the sliding valve so that the two hoods work in unison, a double-acting Critchlow valve is provided. Each of the sliding plates is provided with two air dampers so that it is impossible to shut off the air from the two adjacent pits with the valves in either position. The gas on all four pits is reversed by one three-way valve, but on each side of this valve there are four other valves, so that the gas can be shut off separately on any pit. To reverse the direction of the gas and air, the gas is shut off, then the air reversed, and after it the gas is reversed.

Eight-ingot Pits: The main difference between the six ingot and the eight ingot pits, aside from increased dimensions, lies in the fact that the air regenerators are provided with a special division wall. This wall is built parallel to the end of the pit and extends to the top of the checkers, the object being to retain any cinder running over from the pit in the first few checker openings, thus preventing the choking of all but a few of the checker spaces, and maintaining a higher efficiency of the regenerators. Also, these pits are provided with two cinder holes instead of one as for the six ingot holes. The furnaces are spaced forty-one feet four inches from center to center, and the holes are five feet three inches wide and ten feet seven inches long, and are spaced eight feet three inches from center to center. The covers on these pits can be separated about two-thirds of the distance from the back. On these covers the piston is connected to the end casting of the cover frame instead of to the separator, and there is a separator on each portion of the cover. When closed, the separators fit together and are fastened thus with hooks. With this arrangement it is possible to move the entire cover or, by unhooking, the back portion only may be moved.

Making Up the Bottom of the Pit: Bottom making is done by a group of men called the bottom-makers, who are provided with shovels, long handled pokers and cutters. To clean out a pit, the pit cover is pulled back slightly, and a shield is drawn up over the front of the pit. The cinder hole in the bottom of the pit is then opened with the poker, and by means

of the cutters the cinder is shoved out through this hole. After the cinder has been removed, a piece of iron sheeting is put over the hole, and then the process of making bottom is begun. Coke breeze from the blast furnace coke bins is used to make up the bottom. Coke breeze is used because it absorbs and makes fragile the molten oxide that runs off the ingot, protects the brick work, and helps to maintain a reducing atmosphere in the furnace. The depth of the coke on the bottom should be maintained at about eighteen inches. To provide the desired depth, making up for the coke and cinder that are pushed out each time, requires for each bottom six to eight wheelbarrow loads of breeze, which weighs about 250 pounds per barrow load, for the six-ingot pits; for the eight-ingot pits ten to twelve wheelbarrow loads, or about 2500 pounds, is required. This coke is thrown in from the front, the ends being made up first, the sides next, and lastly the center. The bottom is made up so that there will be two troughs into which the ingots may be placed. The object in providing these troughs is to keep the ingots away from the walls so that they will have a better chance to heat, but at the same time will not be placed so near the center that they will be hit directly by the flame. During the time that the bottoms are being made up, the gas and air are shut off, and the stack is made to draw air through the cover opening so that the heat is drawn away from the men. Before charging ingots on a new bottom, the coke breeze should be allowed to become well heated throughout, as a cold bottom in the pit allows the butts of the ingots to remain cold, and when ingots are put through the mills in this condition they are liable to break the rolls.

SECTION III.

SOAKING THE INGOTS FOR ROLLING.

Charging the Ingots: Ingots should always be charged into the soaking pits in an upright position, which explains the peculiar construction of the pits. There are two reasons for this method of charging. First, the best practice for the care of ingots demands that they be stripped as soon as possible after pouring and delivered to the soaking pits before they lose much of their original heat, because the hotter they are charged the quicker will they reach the rolling temperature, and little fuel for reheating will be required. In pursuance of this practice, most ingots, except high carbon, high sulphur and alloy steels, which are allowed to become solid throughout before stripping, reach the pits while their central portions are still molten and must, therefore, stand in an upright position until this portion has become solid, as otherwise the extent of the pipe might be increased and its position would be changed. Second, by charging ingots vertically more surface for ingress and egress of heat is exposed to the atmosphere of the furnace, thus causing them to come to a uniform rolling temperature much quicker than would be the case if they were placed in any other way.

Heating the Ingots: From what has been said, it is easy to surmise that great injury can be done in the heating of the ingots. This injury consists of under-heating, over-heating, uneven heating, or worse than all, burning. Of these, under-heating and over-heating are the least harmful to the steel; the former increases the power required for rolling and decreases the time permissible for the rolling; the latter, by increasing the grain size and lessening the force of cohesion, makes the steel tender and liable to crack. Uneven heating increases the difficulties of rolling very much. A cold butt of an ingot, for example, may cause a roll to be broken. Burning may range from extreme over-heating to a temperature just below the melting point, where the more fusible constituents melt and run out of the ingot, forming cavities that, on rolling, result in defects that will be cause for rejection of the material. In the case of thin skinned ingots, severe over-heating may have a like result by exposing the blow holes. Besides these general precautions, different conditions and different grades of steel require different treatment. As an example of the point in question a summary of the soaking practice as carried out at Duquesne is given herewith.

Week-end Charges: If hot steel is charged Saturday evening just before the mill shuts down, it will be allowed to soak until one or two o'clock Sunday morning, when gas will be admitted for about an hour. Soaking will then be continued until the day turn comes out. But if cold steel should be charged before the week-end shut-down, gas is admitted for three or four hours, the flame being reversed at intervals of from one-half to one hour; and the steel is then allowed to soak until Sunday morning. During the soaking, the stack and air dampers are kept closed.

Soaking Hot and Cold Ingots: To bring hot steel to the required rolling temperature requires approximately the same amount of time as the interval between the time the heat was tapped and the time it was charged into the pits. Hot special steel of medium carbon content must be in the pits about one and one-half hours and spring steel about one hour. Thus, the period, from the time the heat is tapped at the open hearth until it can be rolled, is about three hours for Duquesne special, about two hours for spring steel, and one and a half hours for ordinary steel. To heat six cold soft steel ingots in the 6-ingot pits requires about six hours. For about four hours after the pits are charged, the gas and air may be admitted on each side alternately for half hour periods. The period of reversal should then be cut to fifteen minutes. Towards the last, as the temperature of the steel approaches the rolling temperature, the period of reversal may be cut to five or ten minutes, for the more frequent the reversal the more even will be the temperature of the pits. Cold steel is very rarely charged in the ingot pits, the practice being followed only after a shut-down when the mills start operating at the same time as the open hearth, for at such a time there is no hot steel on hand. The period required for heating cold steel in the eight-ingot pits is about eight hours.

Soft steel is heated to a temperature of about 1200° C. (2200° F.). With both high and low carbon steels, should only four or five ingots be charged in the smaller pits, the period required for heating would be greatly reduced. This is true especially for the low carbon steel, for with only four ingots to a pit it is possible to prepare the cold steel in four hours. By charging only six ingots in the large pits, the period may be reduced to about six hours. Before a cold high carbon heat (.70% carbon or over) is charged, the pits should be cooled for about a half hour, for if these ingots are heated rapidly they are liable to crack. After the pits have been cooled, the ingots are charged, and sometimes the covers are left open for a half hour, so that the steel will be heated very slowly. The period between reversals should not be as long as for low carbon cold steel, and so at first the reversals for steel of this grade are made at intervals of a half hour or less, and during the balance of the time the period between the reversals is about ten minutes. The rolling temperature of spring steel is about 1090° C. (2000° F.).

Soaking Hot Spring Steel: This grade of steel is charged in a hot pit. The gas may be admitted for a half hour, the flue being reversed every five or ten minutes; the steel should then be allowed to soak for fifteen minutes, and then gas should be admitted for about fifteen minutes to bring up the temperature of the outside of the ingot. This steel should be ready to roll in about an hour. While the steel is soaking, in addition to shutting off the gas, it is best to shut off the air supply, also, for the effect of the hot air on the ingot is to oxidize or even to burn it. If the steel is very hot when charged, it should be allowed to soak for a half hour before gas is admitted; then gas and air should be admitted for about a half hour, with reversals every five or ten minutes. The steel should then be soaked for a half hour without air, and then, just before drawing, the temperature of the outer part of the ingot should be brought up by admission of gas and air again.

Soaking Low Carbon Hot Steel: Hot low carbon steel ingots may be heated without danger for a half hour, the direction of the gas and air being reversed every fifteen minutes. The steel should then be allowed to soak for fifteen minutes, and before drawing the outside temperature should be raised. Since there is not as much danger of burning this steel as there is with the high carbon grades, it is not always necessary to close the air dampers during the time the steel is soaking.

Soaking Medium Steels: The practice with respect to medium steels, .30 per cent to .60 per cent carbon, is to heat the ingots to about the same temperature as for low carbon steel. The steel, if charged hot, should be ready to roll in one hour after charging.

Soaking Screw Stock: High sulphur steel is charged as quickly as possible after stripping. The time required to heat it is about one and a half hours. The steel is heated to dripping, that is, until the scale melts and flows readily from the surface, and is rolled when in that condition. Owing to the high sulphur content, it is necessary, to maintain good practice

in rolling, to heat it very hot, so that the steel will be very plastic. This condition is obtained only at a very high temperature, about 1240° C. (2240° F.). Since these screw stock ingots are heated until they are dripping, a large amount of liquid cinder is always formed, so that it is necessary to add a little coke in the pits after every heat of this kind to absorb this cinder.

Soaking Alloy Steels: Nickel steel is heated to about the same temperature as spring steel, 1090° C. Chrome vanadium is heated to about 1250° C. Copper steel is heated according to its carbon content in much the same way as carbon steels.

Drawing the Ingots: The craneman draws the ingots from the pits according to the orders of the heater. Usually, a definite order is followed; at Duquesne the regular method is to draw the two front ingots from each of two holes, then the two middle ones from each of the two holes, and then the two back ones from each of the two holes. The operation is then repeated on the next two holes. However, the operation may be varied; the two front ones in each of four holes may be drawn, thus affording more time for the middle ingots to heat while the others are being drawn. To transfer the ingots from the pits to the blooming mill tables three pot cars, two of which are extras, are provided. These cars are operated by 19 h. p. Westinghouse motors. At the 38-inch mill they are controlled and dumped by the manipulator man of the mill, but on the 40-inch mill, the man that operates the pit covers controls the movement of the car. When the car receives an ingot it is run to the first table roller, and there the car is tipped, when the ingot falls upon the table.

Heat Balance of Pits: That the soaking of ingots is an expensive process is evident from the equipment required. The cost of the up-keep of this apparatus is high, and the efficiency is very low, even on up-to-date furnaces, as the following heat balances as determined by experiment on some Duquesne furnaces using natural gas will show:

Table 59. Data Relative to the Efficiency of Soaking Pit Furnaces.

Sensible Heat in Steel Charged	619,701 B. t. u.
Heat of Combustion of the Gas	781,808
Heat Carried in by Regenerated Air	384,970
TOTAL	1,786,479

Heat in Steel when Drawn	773,597 B. t. u.
Heat in Gases Entering Stack	173,862
Heat Given up to Regenerators	386,329
Radiation and Unaccounted for Losses	452,691
	1,786,479

$$\text{Pit Efficiency} = \frac{\text{Heat Absorbed by Steel}}{\text{Total Heat Delivered to Furnace}} = \frac{153,896}{1,786,479} = 8.6\%$$

Disposition of Ingot Products: Since the ingot is the starting point for all mechanical working, it is interesting to trace the material through the various processes that the steel undergoes to produce the many articles in which it is used. For this purpose the following table has been prepared, and requires little by way of explanation. Each dash marks a reheating of the material, while each word means a mill, or a set of mills, where work is done to produce the article named.

Table 60. Disposition of Steel from Ingots.

- Ingots
  - Universal Mill Plate.
  - Armor Plate.
  - Bloom, Sheet Bar—Sheets.
  - Shaped Bloom, Large Shapes.
  - Slabs
    - Universal Mill Plates.
    - Eye Bars.
    - Sheared Plates.
  - Bloom, Billet
    - Rods.
    - Bars.
    - Bands.
    - Hoop.
    - Small Shapes.
  - Rectangular Bloom
    - Billet
      - Rods.
      - Small Shapes.
      - Bars.
      - Bands.
      - Seamless Tube.
    - Sheet Bar—Sheet.
    - Structural Shapes.
    - Rails.
    - Rail Joints.
    - Skelp
      - Tube.
      - Pipe.
    - Forgings.
  - Cylindrical Blooms
    - Wheels.
    - Circular Shapes.
    - Shell.
  - Large Forgings.

CHAPTER V.

THE ROLLING OF STEEL—BLOOMS AND SLABS.

SECTION I.

INTRODUCTORY.

Outline of the Plan of Study: Rolling mills are somewhat like houses. Thus, while they are alike as to gross features, they differ greatly as to details of construction. Just as the architect will strive to impart individuality to a building, so the rolling mill engineer and builder will endeavor to introduce new ideas looking to greater improvements in construction; and just as it is desirable to adapt a building to its location and surroundings, so is it found necessary to alter the details of mill construction to suit the conditions, local and otherwise. The result of all these influences on mill construction has been to produce such a variation in mills that there are no two mills exactly alike. Evidently, to describe all the details of mills and their operations is well nigh an endless task; yet it is desirable that the reader be given an opportunity to become so well acquainted with the rolling of each product, or each class of products, that he will be more or less familiar with the more essential details of its production and have some understanding of the conditions under which it is produced. The plan decided upon as best to pursue is this: An attempt will be made to describe the rolling of as many products as possible, and in doing so the order followed will be from the rolling of material from ingots, to semi-finished products, to finished products, as indicated in the previous diagram. In this connection one mill rolling the material in question will be described, as well as the operation in detail; after which the product itself will receive special attention. In describing mills, the details of one mill of each type or class will be given. As a sort of working outline of the plan, the following classification of mills will give an idea of the ground to be covered and the order in which the subjects are to be treated. The general discussion preceding this part of the study should supply information to fill in any gaps that may occur in the studies to follow.

Table 61. Classification of Mills.

A. Mills Rolling Material from Ingots.
   1. Semi-finishing Mills:
      a. Blooming (Cogging) Mills.
      b. Slabbing Mills.
   2. Finishing:
      a. Universal Plate Mills.

B. Mills Rolling Material from Blooms and Slabs.
   1. Semi-finishing:
      a. Billet Mills.
      b. Sheet Bar Mills.
      c. Skelp Mills.
   2. Finishing:
      a. Plate Mills:
         i. Sheared.
         ii. Universal.
      b. Rail Mills.
      c. Structural Shape Mills.
      d. Wheel Mills—Schoen Mill.
      e. Wheel and Circular Shape Mills.

C. Mills Rolling Material from Billets.
   1. Merchant Mills.
      a. Guide Mills.
      b. Bar Mills.
      c. Hoop or Strip Mills, etc.
   2. Rod Mills.
   3. Piercing (Tube) Mills.

Blooms, Slabs and Billets: As a preliminary step toward forming steel into the various sections which its many uses require, the heavy ingots, except in certain plate mills and some large shape mills, are first roughly reduced, in mills especially designed for the purpose, to much lighter but still very simple sections, as the round, the square and the rectangle. When the ingot has been reduced to the dimensions of a square between one and one-fourth inches and six inches it is cut into convenient lengths, called **billets**; if these pieces are six inches square or larger, they are known as **blooms**: and if reduced to rectangular forms but with widths which are less than twice the thickness and within the dimensions specified for the square, the same names apply. But if the width far exceeds the thickness of the rectangular section, then it is called a **slab.** If the output of the mill is mainly blooms, it is called a blooming mill in the United States or a cogging mill in England; if billets, a billet mill; and if slabs, a slabbing mill. The blooming and slabbing are the largest and strongest mills used to roll steel, if the mills that roll heavy armor, of which there are no longer any in this country, be excepted. The reasons for the existence of these mills are evident.

SECTION II.

SOME GENERAL FEATURES PERTAINING TO BLOOMING MILLS.

Size of Blooming Mills: The size of blooming mills is popularly supposed to be based on the diameter of the rolls, or on the distance from center to center of the rolls. Both these quantities are constantly changing, due to the wearing of the rolls, which affects their diameters, and to the fact that they are adjustable. The size is, therefore, based on the distance from center to center of the pinions, which corresponds to the distance from center to center of the rolls and also to their diameters, and is always constant. The blooming mills in use at the present time will range in size from thirty-two to fifty-four inches. The older mills are the smaller, because it was formerly the practice to cast the ingots much smaller than at present, and large mills were not required. The size of ingots having been gradually increased for the reasons already pointed out, the size of the mills designed to roll them were necessarily increased also. Hence, most mills of recent construction have rolls in the neighborhood of forty inches in diameter, but some of the latest mills, designed to roll heavy shaped blooms, are fifty-four inches in size.

Blooming Mills, Their Advantages and Disadvantages: Blooming mills are of three general types, namely, **reversing, continuous,** (both of which are two-high) and **three-high.** Of these, two-high reversing and three-high mills are the most common. As an example of the continuous blooming mill, the billet mill at Gary, Ind., is cited. It consists of nine stands of rolls arranged in tandem and separately driven by electric motors. Since its blooms are delivered directly to a continuous billet mill, the reduction of the ingot to billets is made in one continuous operation. The chief advantages in this arrangement over the three-high single strand is an extraordinary large output and the greater sturdiness of the two-high stands. As to reversing and three-high bloomers, each of these types has its advantages and disadvantages, some of which it may be of interest to enumerate here. The main advantage of the reversing mill over the three-high lies in its greater flexibility. Thus, the top roll being adjustable, various sizes of blooms, billets or slabs can be rolled on one set of rolls, and the draught can be regulated to suit steel at different temperatures and of different grades. Even different methods of reducing the ingot may be employed with the same rolls. On long lengths the two-high mill is to be preferred on account of the greater ease with which such material can be handled, while the simplicity of the roll design is also a factor in favor of these mills. On the other hand, a reversing mill is a much more expensive mill than a three-high mill. In the first place the tonnage is much lower. On two-high forty-inch mills the average output is about 2000 tons per twenty-four hour day, to produce which about 2500 tons of ingots are

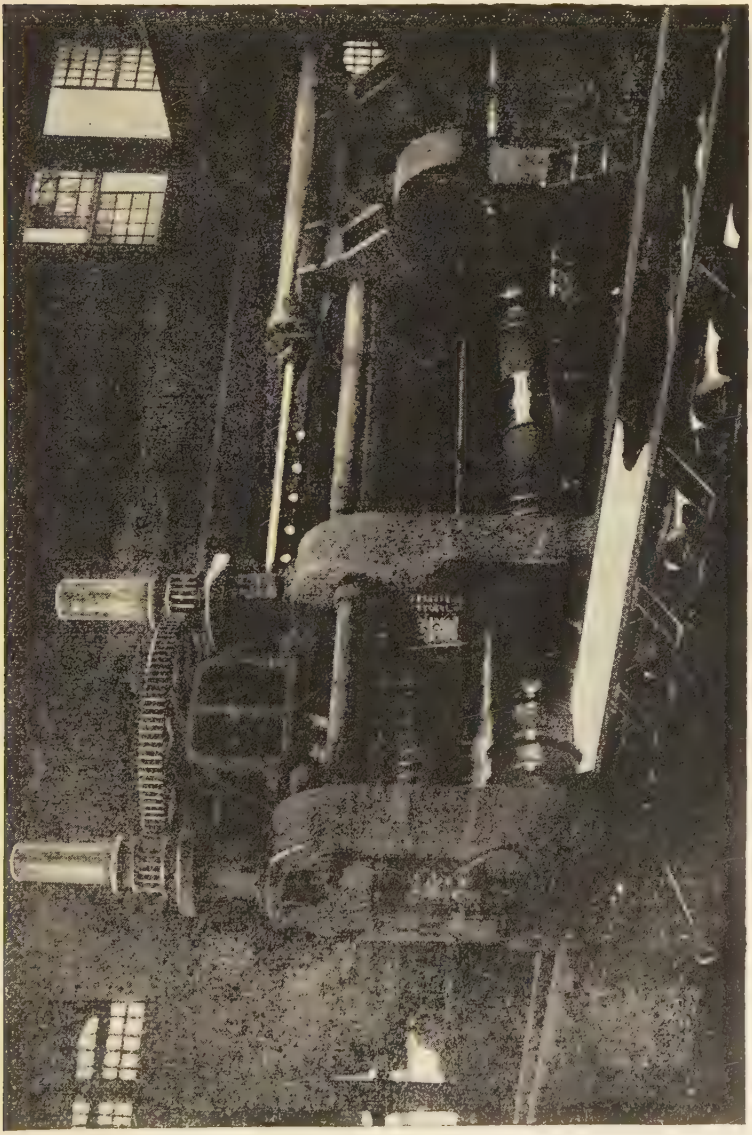


FIG. 126. View of 38-inch Reversing Blooming Mill in Operation.

required, while a three-high mill of the same size will roll almost twice as much steel. Again, the power equipment of the reversing mill is costly and the loss of power is great. Reliable tests show that the total power developed by a reversing mill engine is distributed about as follows:—

27% used in overcoming idle friction of the engine parts.
9% used in overcoming pinion and spindle friction.
13% used in overcoming roll journal friction.
21% used in overcoming the acceleration of the parts in reversing.
30% used in actually deforming the steel.

In three-high mills where the rotation is in one direction only, there is no acceleration loss, besides, by the use of a flywheel, lighter engines than those used on the reversing mill may be used to do the same work. Efficiency tests on three-high mills show that about 85 per cent. of the total power developed by the engine is used in driving the mill, and the idle friction of the mill parts is about 15 per cent., thus leaving nearly 70 per cent. of the motive power developed available for deforming the steel.

Drive for Reversing Mills: Since the lengths dealt with on blooming mills are relatively short, the speed of the rolling is slow, but as the material is heavy and the pull is great, though the draughts are only moderately heavy, great power is required. Hence, most of the older reversing blooming mills are indirectly driven, that is, they are connected to the engine through large gears which enable the engine to travel at a higher speed than the mill. The power is thus multiplied by a number equal to the speed ratio. This speed ratio will vary in the different mills from as high as three to one to as low as one to one, while many mills, of which the thirty-eight-inch bloomer at Homestead and the forty-inch mills at Clairton and Duquesne are examples, are direct driven. A few reversing mills installed since 1914 are driven by reversing electric motors. These motor installations are very complicated. They consist of a main motor and a motor-generator set, which prevents the acceleration loss peculiar to the steam driven reversing mill and raises the efficiency of the mill considerably.

SECTION III.

AN EXAMPLE OF REVERSING MILLS—THE 40-INCH MILL AT DUQUESNE.

The Engine for this mill, which is driven direct, is of the twin tandem compound condensing type, but is operated non-condensing. It was made by Mackintosh-Hemphill & Co. Its size is 44″ x 70″ x 60″ and its maximum horse power is rated at 20,000. The maximum torque at the circumference of a thirty-inch roll is 465,000 inch-pounds. The engine may run at any speed up to 140 r. p. m., but the maximum speed during rolling is about

130 r. p. m. The exhaust steam is discharged into a feed water heater. The throttle is controlled from the pulpit located about thirty feet in front of the rolls and directly over the roll tables.

Driving Connections: A cast nickel-steel crab of six pods is keyed onto the crankshaft of the engine; it is four feet five inches in diameter. Over it, and held in place by wooden stretcher blocks, is fitted the large end of a cast nickel steel compound coupling box, which, at this end, is three feet two inches in diameter. The driving spindle from this coupling is five feet eleven and one-fourth inches long, and is supported by a cast steel coupling carrier resting at its four corners on standard spiral car springs of 12500 pounds capacity, which stand eight and one-fourth inches high when free, seven and one-fourth inches at 4700 pounds load, and six and nine-sixteenth inches when fully compressed. The springs in turn rest on cast steel seats bolted to special cast iron shoes which are anchored to the shoes carrying the pinions and housings. The carriers are lined with one inch of babbitt metal. The mill end coupling box is two feet four and one-half inches in diameter, and is cast to fit over the four pods of the engine-end wobbler of the bottom mill pinion.

Pinions and Pinion Housings: The pinions are of the staggered straight tooth type and are made of nickel steel, approximately of a composition as shown by the following analysis: Carbon, .29%; manganese, .66%; phosphorus, .020%; sulphur, .030%; and nickel, 2.97%. Their average life is 253,575 tons of steel rolled. The top and bottom pinions are similar, hence interchangeable. Each one is ten feet six inches long over all and four feet ten inches between the necks, which are twenty-one inches in diameter. This diameter is further reduced to twenty and one-half inches at the wobblers. The pitch diameter is forty inches, and the number of teeth is fourteen. The pinions run in solid cast steel babbitted bearings, the bottom of which are beveled to fit on the sills of the window of the cast iron pinion housings. The pinion housings are bolted to the mill shoes, are nine feet six inches high, and have windows 2′ 7½″ wide by 7′ 6½″ deep; the windows are lined with one and one-fourth-inch forged steel liners held in place by stud-bolts through the housings. A cast steel housing cap, to which is attached the hydraulic cylinder used for lowering the top roll of the mill, is fastened over the housings by means of key bolts. The bearings are each two feet six inches wide and twenty inches from front to back and may be adjusted by set pins reaching through the housings. The top bearings rest directly on top of the bottom bearings unless plate liners are used in between them to get the proper pitch for the teeth. The bearings are held down tight by keying the cap on tight and using liners between it and the top bearing if necessary.

Spindles and Coupling Boxes: Over the mill-end wobblers of the pinions are fitted cast steel coupling-boxes uniting the wobblers with the spindles. These coupling boxes, are two feet six inches in diameter

and twenty-two and one-half inches wide, and cast to fit over the four pods of the spindles. The bottom and top spindles are each ten feet long and twenty-one inches in diameter where they rest on their carriers. The bottom spindle is provided with wobblers twenty and one-half inches in diameter and two feet in length, and is nineteen inches in diameter at the center between the two carrier bearings. On the top spindle the wobblers are nineteen inches in diameter, thirteen and seven-eighths inches long and are curved at the ends to permit the mill end to ride up or down with the top roll. Twenty-three inches at the center of the top spindle is turned smooth to a diameter of twenty-one inches to give a bearing for the spindle carrier, which is movable. The bottom spindle rests at two points near its ends on two stationary spindle carriers bolted to the mill shoes. The carrier for the top, or vibrating, spindle consists of a cradle formed by two cast steel arms hung at their engine ends from two supporting rods pivoted on spring-supported bolts which pass through supporting brackets bolted to the pinion housings. In the center of the carrier is a rest for the spindle, and on its mill end the carrier is supported by the carrier bearing for the top roll, being fastened to this bearing by a forged steel pin. A coupling-box similar to those used with the pinions fastens the bottom spindle to the bottom roll; seven-eighths of an inch clearance is allowed at each connection between spindle and pinion or roll, respectively. For the top pinion, a light coupling box is used in order that it may act as a safety for the mill by breaking under excessive strain before any other part of the mill is damaged. This box is twenty-two and one-half inches in width, twenty-five and three-fourths inches in outside diameter, and two and one-quarter inches in thickness at the thinnest point. The other boxes are four inches thick. All coupling boxes are held in place by iron or wooden stretcher blocks fastened in place by steel or leather straps.

Roll Housings: The roll housing on the engine side of the mill is set with its center-line fourteen feet six and one-quarter inches from the center line of the mill-end pinion housing, a cast iron separator and steel bolt holding these two housings in line. This housing is cast steel but in other respects is the same as the outside housing, which is made of cast iron. Both are bolted to the mill shoes and stand twelve feet three inches high above them; they are set with their center lines seven feet eleven inches apart and are held in line by two cast iron separators and steel bolts, one at the front and one at the back. Besides the mill rolls, the housings also support four feed rollers, two on each side of the rolls, sixteen inches in diameter and five feet ten and one-eighth inches long. The windows of the housings are three feet five and one-half inches wide, nine feet deep, and begin two feet ten inches below the top of the housing. In the top of each housing is left a hole for the housing nut, which is made of brass. Through these nuts the housing screws for adjusting the top roll are inserted. The nuts are larger at the bottom than at the top; they are twenty inches in diameter at bottom, sixteen inches at top, and thirty-four inches high.

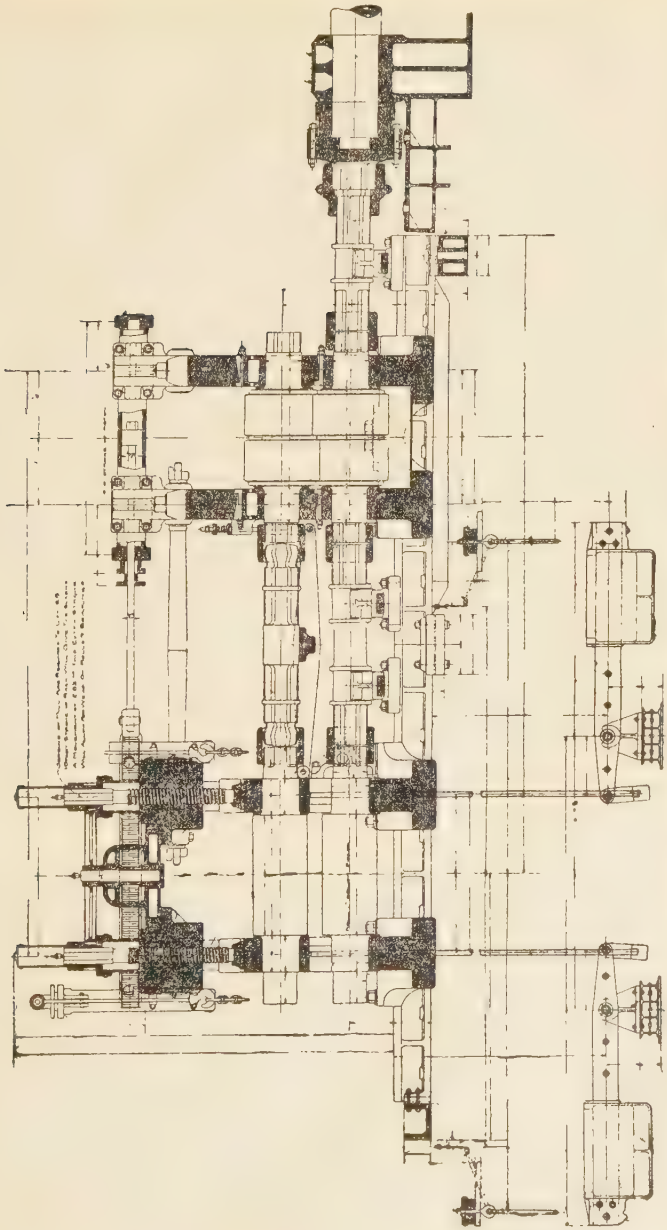


FIG. 127. Longitudinal Section Through Rolls and Pinions of a 40-inch Reversing Blooming Mill.

They are shrunk into the housings, and over them are fastened small caps, twenty-seven inches high, on which the screw pinions rest. The housing screws, the bottom ends of which press directly down on the screw brasses in the cast iron breaker blocks on the rider bearing boxes of the top roll, are made of .60 per cent. carbon open hearth steel, eight feet three inches long and ten inches in diameter; the threads have a pitch of two inches. They must allow a lift of twenty-five inches. These screws are provided with octagon heads. Fitted about the heads are steel pinions which rest on the top of the screw caps. The pinions have a pitch of two and one-quarter inches, a pitch diameter of fifteen and eighty-two-hundredths inches, a face of eight inches, and twenty-two teeth. The pinions are operated through a gear mounted on a spider which has a pitch diameter of eighty-three and nine-hundredths inches, a pitch of two and one-fourth inches, a face of seven inches, and one hundred sixteen teeth, and is, in turn, operated by means of a pinion fastened to its shaft. This latter pinion has a pitch diameter of twelve and fifty-four-hundredths inches, a pitch of three inches, a face of ten inches, and thirteen teeth, and is operated by a rack with a three-inch pitch and a ten-inch face. This rack is connected up to the hydraulic cylinder located on the top of the pinion housing. Attached to the rack is the finger, which, moving over a gauge, provides an indicator for the size of the pass. The screws of the mill are required to lift twenty-five inches, but a ten-foot stroke of the rack will give the screws a vertical movement of twenty-eight and one-half inches, the extra length of stroke allowing for the wear of the roll necks and bearings. In rolling, this gauge can be set to give correct readings on one pass only, and to gauge the other passes it is necessary to add or subtract a certain quantity from the gauge reading. A cast iron bridge is bolted to the top of the housing and serves both to support the spider and to keep the housings properly spaced. The housings are further supported and kept in line at the top by two cast iron separators and two steel bolts.

Rolls: The top and bottom rolls in this mill are alike; there are two in a set, and each roll weighs 26,000 pounds. A typical analysis of the rolls gives the following results: .61% carbon, .75% manganese, .010% phosphorus, .030% sulphur. Their dimensions are: Total length, twelve feet ten inches; length of body, six feet; diameter of wobbler, twenty and one-half inches; diameter of necks, twenty-two inches; diameter of collars, thirty-three and one-eighth inches. They have five passes, the widths and diameters of which are 24″ x 31⅝″, 12″ x 29⅛″, 8″ x 29⅞″, 6″ x 29⅝″, 4″ x 29⅝″. The rolls are ragged only in the twelve-inch and eight-inch passes, and here the ragging is only one-sixteenth of an inch deep; all passes are roughened slightly with knurling wheels. These rolls are changed every week and dressed in the roll shop. About three-sixteenths of an inch is taken off each time they are dressed, and when the collars have been cut down to thirty and one-half inches, the rolls are scrapped. Four sets are

kept on hand, and one set is used once in four weeks, giving a life of about one year per set. The average tonnage is 82,650 tons for each set of rolls.

Roll Bearings: The bottom roll rests with each neck on a babbitt lined cast steel bearing, two feet six inches wide, twenty-one and three-fourths inches from front to back, and six and three-fourths inches thick at the base; its bottom is made to fit the sill of the window, and its top is cut out at a twelve-inch radius with one and one-quarter inches of babbitt to fit the neck of the bottom roll. Sheet steel shields are placed over the necks of the bottom roll to keep scale from getting between the necks and bearings. The top roll is carried in two cast steel carrier bearings, which in turn are supported each by two three and one-half-inch square steelyard rods. These rods are mounted in sockets hung from counterweighted arms underneath the mill, the rods coming up through the housings and bottom bearings on each side of the necks of the bottom roll. The carrier bearings are three feet three inches wide, twenty-three and three-fourths inches from front to back and are six inches thick at the base. They are flat on the bottom and concave at the top with a twelve-inch radius and babbitt metal one and one-fourth inches thick. On the engine side of the inner bearings are two lugs for receiving the pin to hold up the spindle carrier. The rider bearing of the top roll is cast steel two feet two and one-half inches wide, twenty-one and three-fourths inches from front to back, and two and one-fourth inches thick, with one inch of babbitt metal. It is concave below at a radius of twelve inches and beveled on top. The bearing box, also of cast steel, is of the same dimensions as the bottom bearing, except that it is seven inches thick. It is beveled underneath to receive the top bearing and is flat on top. On it rests the cast steel breaker block, into which the housing screw fits. The breaker blocks are protected by brasses, which are placed in sockets on the tops of the blocks.

Hydraulic Shears: Immediately beyond the forty-inch mill delivery table, begins the No. 1 shear table, delivering to a hydraulic bloom shears. This table is thirty-one feet long, and consists of fourteen cast steel rollers, twelve inches in diameter and five feet eleven and one-quarter inches long. These are driven by a Westinghouse 30 h. p. 220 volt series wound D. C. motor, controlled either at the bloom or the billet shears. At the end of this table is an emergency shear. It is a vertical hydraulic shear, using water at 500 pounds pressure to the square inch; the plunger is forty-two inches in diameter with a nineteen-inch stroke. The bottom shear knife is the one actuated by the plunger; the knives are twenty-seven inches wide and four inches thick. As this is an emergency shear, it is rarely used.

Steam Shears: No. 2 shear-table is immediately beyond the hydraulic shears and has thirty-six driven rollers, and one idler, all similar to those at No. 1 shear-table, except the last two, which are collared on one end. The rollers are driven by a Westinghouse 50 h. p. 220 volt series wound D. C. motor controlled at the steam shears. This table delivers the blooms and

slabs to the steam shears, the center of which is ninety-two feet ten and one-half inches beyond the hydraulic shears. A bloom stamping machine is located on this table midway between the two shears; it is of the idler wheel type and is held in place hydraulically. The steam shears are driven by a Mackintosh-Hemphill 18″ x 20″ simple vertical steam engine, the driving shaft of which is meshed with the shears by a hydraulically operated clutch. These shears are also vertical acting, the top knife blade being driven down to meet the fixed lower one. The knives are twenty-seven and one-half inches wide and three inches thick, and the top one has a ten and three-fourths-inch stroke. The steam shears are equipped with a gauge and stopper for cutting a number of pieces the same length; the stopper can be set to cut lengths from twelve inches to one hundred thirty-six inches, inclusive, in quarters of an inch; the piece to be cut is run through the shears onto the rear table, which is sixteen feet long and consists of sixteen hollow cast steel rollers, ten inches in diameter. It is driven through universal joints by a Westinghouse 19 h. p. 220 volt series wound D. C. motor and can be tilted at its receiving end hydraulically to move down with the shear knife. For pieces forty inches long or less, it is moved nearer the shears to prevent the piece from falling into the pit for butt ends. Beyond this table is the loading table for blooms and slabs; it is seventeen feet long and has sixteen hollow cast steel rollers eight inches in diameter. It is driven from a line shaft by the same type of motor as the shears rear table. Halfway down this table on its inner side is a steam kicker with a seven-inch by four feet nine-inch cylinder, which slides the bloom down a chute to the buggies on the tracks below. A hydraulic stopper is located at the end of this table. Crop ends or scrap can be run over the end of the table to charging boxes below the end of it. Six feet six inches beyond the end of this table begins the receiving table of a fourteen-inch continuous mill.

Manipulator: All reversing mills are provided with manipulators for turning the ingot as desired between the passes, for moving the piece from groove to groove and for straightening it as it enters the passes of the mill when such straightening is necessary. They are located under the roll table, and near the rolls on the entering side of the mill. They are of various forms. The original manipulator for this mill consisted of two parallel sets of five fingers each, and had both a vertical and a horizontal movement. The frame was beneath the table rolls and rested on a bottom frame which was supported on four heads, connected to the arms of bell cranks. These cranks were supported on a bed plate and were connected up by stretcher rods to a hydraulic lifting cylinder, which had a stroke of fourteen and three-fourths inches. This ratio of the length of the crank arms, however, increased this lift to eighteen inches. On this frame were five rails to form a track for the wheels of the upper frame which was moved horizontally by means of a hydraulic cylinder. In the lowest position, the fingers were five inches below the top level of the roll tables;

in the highest, they extended thirteen inches above it. This manipulator was replaced in 1924 by one of a different type, but the description above will serve as an example of the mechanism of these devices.

Design of the Rolls: All reversing blooming mill rolls are designed with slight collars between the passes in order to control the spreading of the material under the heavy reduction, as otherwise the material may spread so far at the surface as to cause a protrusion, or fish tailing, of the metal at the edges, which, becoming folded over, would cause laps. To prevent the collars from cutting into the steel and thus forming laps all the passes except the finishing are given a slight belly. A fillet at the base of the collars serves to keep the corners of the piece well rounded. The ragging on the rolls to increase the bite has already been referred to. As to arrangement of the passes, different plans may be pursued, as may be seen from a study of the accompanying drawings. The first two designs are for blooms, billets or slabs, whereas the third design can roll large blooms only and billets only in connection with a roughing mill.

In the method shown in table 62 and Fig. 128 the reduction is begun with the ingot on edge, but when rolling soft steel, .08 per cent. to .22 per cent. carbon, the ingots are sometimes rolled on the flat. This reduces the number of passes to seventeen, the steel receiving only four passes in the first groove. In rolling blooms of other sizes and slabs, about the same procedure is followed out, the steel being given a sufficient number of passes to work it down to the required size. In rolling some of the special steels, such as special drop forgings, etc., it is often the practice to turn the steel after each pass in order to avoid all danger of rolling in laps and seams. Sometimes where fairly sharp corners are desired on the blooms, they are given extra passes to hold the edges up. This extra rolling is especially necessary where the blooms are to be reheated in a continuous furnace, since if the corners are very rounded the blooms, instead of sliding down, are liable to roll over the skids in the bottom of the furnace. Furthermore, if the steel shows a tendency to crack, the roller may nurse it along by taking lighter drafts.

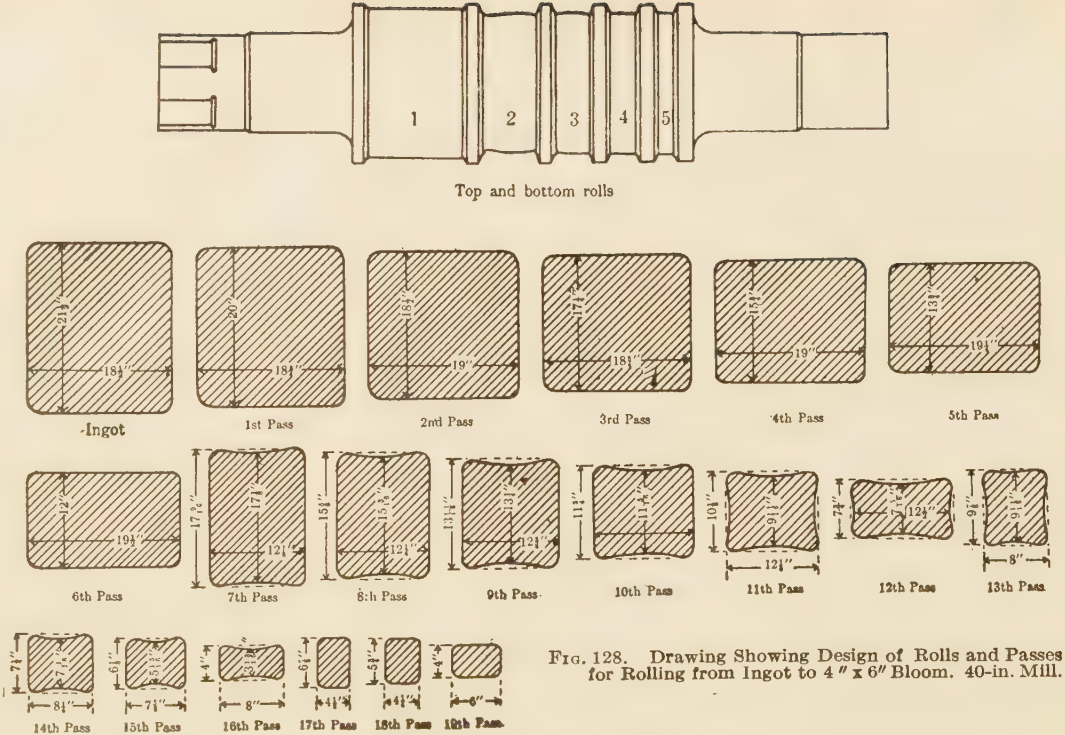


FIG. 128. Drawing Showing Design of Rolls and Passes for Rolling from Ingot to 4″ x 6″ Bloom. 40-in. Mill.

Operation of Rolling: The sketch referred to above shows how an 18″ x 21″ ingot is broken down to a 6″ x 4″ bloom in nineteen passes. This sketch, combined with the following table, gives about all the information there is to give on this part of the work.

Table 62. The Rolling of an 18″ x 21″ Ingot.

No. of Groove	Size of Groove on Roll	No. of Passes and Manipulation	18″ x 21″ Ingot Reduced to
1	24″	2 —Bloom turned 90°	18½″ x 19″ Bloom
1	24″	4 —Bloom turned 90°	12″ x 19½″ "
2	12″	4 —Bloom turned 90°	11¾″ x 12½″ "
2	12″	2 —Bloom turned 90°	7¾″ x 12½″ "
3	8″	2 —Bloom turned 90°	7½″ x 8¼″ "
3	8″	2 —Bloom turned 90°	4″ x 8″ "
5	4″	1 —Bloom turned 90°	6⅞″ x 4⅛″ "
4	6″	1 —Bloom turned 90°	5¾″ x 4¼″ "
4	6″	1 —Finish	4″ x 6″ "
		19 Passes	

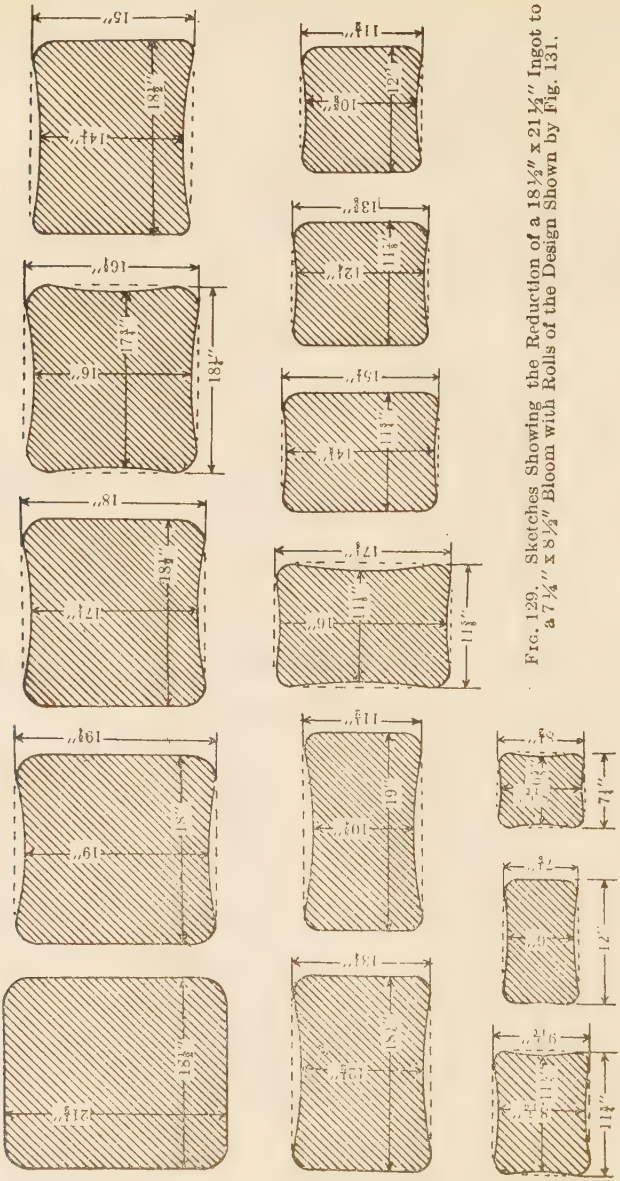


Fig. 129. Sketches Showing the Reduction of a 18½" x 21½" Ingot to a 7¼" x 8½" Bloom with Rolls of the Design Shown by Fig. 131.

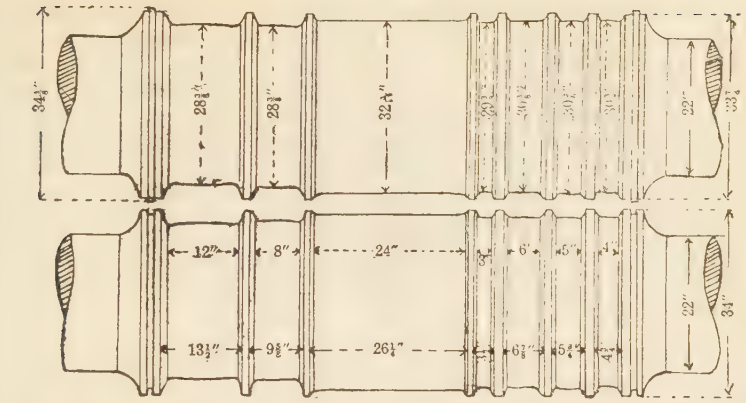
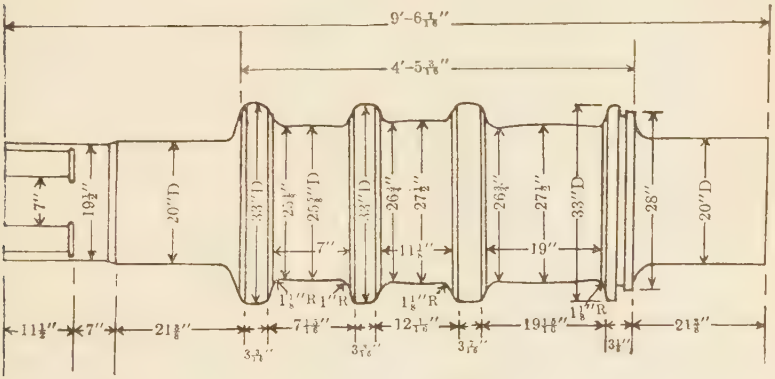


Fig. 130. Another Design for 40-Inch Two-High Reversing Blooming Mill Rolls.



Top and bottom rolls have same dimensions

Fig. 131. A 38-Inch Reversing Blooming Mill Designed to Roll a Fixed Size of Bloom.

SECTION IV.

EXAMPLES OF THREE-HIGH BLOOMING MILLS.

Plan of Study: Since a good idea of the relative dimensions of the different parts of the blooming mill may be gained from the preceding detailed description of the forty-inch mill at Duquesne, such details, for the sake of brevity, may now be omitted, and the description of the forty-inch three-high mill at Edgar Thomson be made more general with the idea of emphasizing the difference in construction and operation between the two-high and the three-high blooming mills, only.

The Engine and Connections: A tandem compound condensing engine, size 50″ x 78″ x 60″, furnishes the driving power for the mill. The engine is housed in an engine room separate from the mill. It is provided with a 75-ton flywheel, twenty-five feet in diameter, and runs at a speed of 54 r. p. m. This flywheel, supported between suitable bearings, is mounted upon the driving shaft, which is connected, by means of a crab and coupling box, to the driving spindle. This spindle is nine feet eight and one-half inches long, including ten inches at each end for the wobblers, and twenty-one and three-fourths inches in diameter. It is supported at its center by a stationary carrier bearing, and, extending through the wall of the separate engine room, connects the driving shaft of the engine to the middle pinion of the mill.

The Pinions and Spindles: The pinions, contained in three-high housings similar to the roll-housings, are six feet four inches long over all, and, when in place, measure forty inches from center to center of any two adjacent ones. The lengths of the necks are twenty-one inches and their diameters are twenty-two inches. These pinions are of the herring bone, or helical toothed type. Unlike the reversing mill, where the use of a vibrating spindle makes it necessary to set the pinions at some distance from the mill, the three-high mill will be set with the pinions as close as possible to the rolls; the roll spindles are, consequently, much shorter. The spindles for this mill are four feet ten and three-fourths inches long over all, and twenty-one and three-fourths inches in diameter. Each spindle is supported at its center by means of a bearing mounted on a bar that bridges the space between the inside roll housing and the opposite pinion housing. Specially designed coupling boxes connect the spindles with the pinions and the rolls.

The Roll Housings are of the open top type. At the top the window of the housing is closed with a heavy cap, which is securely fastened to the columns of the housing by means of heavy key bolts, the slotted ends of which extend up through and above the ends of the cap. The screw down passes downward through the center of the cap and rests on the top of the upper bearing of the top roll, so that the pressure may be applied directly over its center. The rigidity of the housings is increased by the use of brace rods which extend from a height about the center of the top roll, both fore and aft, to an anchorage provided by projections on the shoes. The two housings are tied together by means of separators and bolts on front and back attached just below the caps of the housings, so that they are almost on a level with the upper side of the top roll. In width, the housings measure seven feet eight inches from center to center of the shoes, and are approximately fourteen feet high from the lowest point in the base to the top of the cap.

The Rolls are all of the same length and diameter of neck. The lengths of the bodies are seventy-six inches, while the dimensions of the necks and

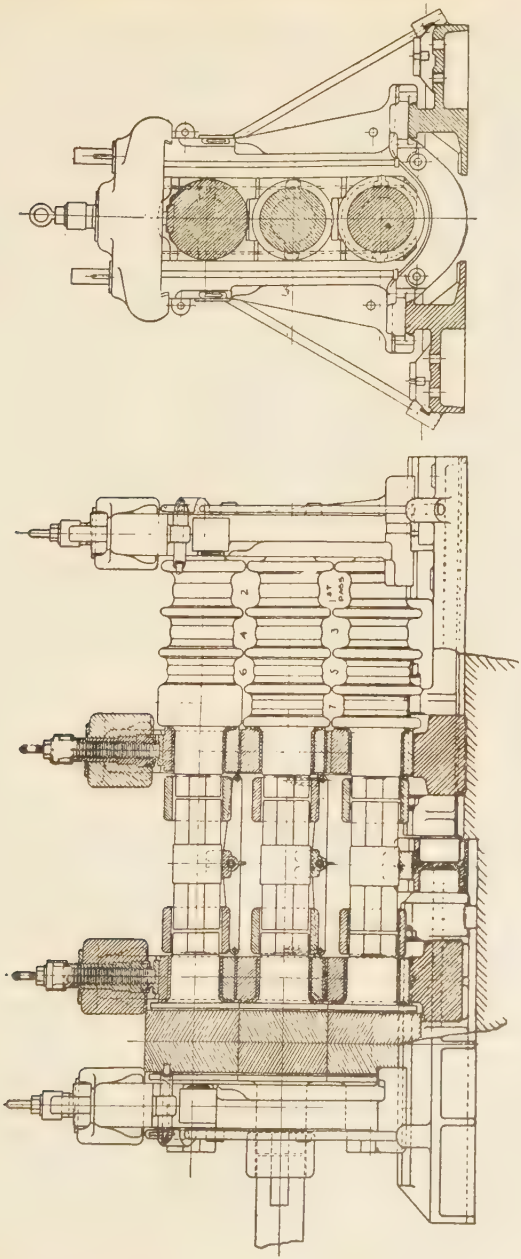


FIG. 132. Sketch of Three-High Blooming Mill.

wobblers are the same as for the same parts of the pinions. As to the diameters of the bodies, the three rolls are made different, the top roll being the smallest and the bottom roll the largest and the middle roll of an intermediate size. These diameters are such that the distance between the centers of new rolls on new bearings is forty and fifteen-sixteenths inches for the bottom and middle rolls and thirty-nine and eleven-sixteenths inches for the middle and top rolls. This arrangement, the necessity for which will be explained later, has the effect of throwing the rolls slightly out of line with the pinions which measure forty inches from centers to centers. This difference is distributed by centering the bottom roll five-sixteenths inch below the center of its pinion and the top roll five-sixteenths inch above the top pinion. The center of the middle roll is then five-eighths inch above that of the middle pinion. The rolls are designed for seven passes as shown on the accompanying sketch. The ingot, having been reduced from 23⅝″ x 23⅝″ to 15½″ x 18¼″ by four passes on a forty-eight-inch two-stand tandem bloomer, enters the first bottom pass of the forty-inch mill on edge and is reduced in this and the six succeeding passes to a 9½″ x 9½″ bloom. Hence, all the mills of the plant using blooms from this mill are adjusted to take this size of bloom. It will be observed that the edges of the collars are well rounded off to prevent the formation of fins that might cause laps, and that the pitch line for the bottom passes lies well below the clearance line of the rolls. The bottom and middle rolls are made of steel, while the top roll is a sand roll. The greater strength of the two lower rolls is required for the greater draught taken in the bottom passes, which are edging passes.

Lifting Tables: The mill is provided with two lifting tables, each of which is twenty-one feet seven and nine-sixteenths inches long from center to center of the first and last rolls. Each table has a vertical motion only, and is supported on four legs or vertical shafts, one at each corner, which are connected to lever arms mounted on shafts with other arms for counter weights and lifting. The torque of the counter weight just about equals that produced by the table. The material is then raised and lowered by a reversing electrical motor, which is provided with a magnetic brake for automatically stopping the tables at the correct levels. By means of a long lever arm, the two tables are connected and are raised and lowered in unison. The one on the approach side of the mill is provided with stationary vertical skid bars, or transfer fingers, between the table rolls, which are so arranged that the act of lowering the table edges and transfers the piece to the next bottom pass. The bloom from the forty-eight-inch mill is edged to enter the forty-inch mill by means of single collar rolls. Shears of the side cutting type, electrically operated, are provided fifty-six feet from the roll table for cutting the piece into blooms of the desired length after the required discard has been sheared off.

Roll Design for Three-high Bloomers: The peculiarities, previously pointed out, in the size, the arrangement, and the grooves of the rolls for this mill are common to three-high bloomers, and represent the effort on the part of the designers of the rolls to overcome certain difficulties inherent in this type of mill. First, in order to avoid weakening the rolls by increasing their length unduly, only a small number of passes, usually nine, are available. Second, except at rail mills, which are the only mills in existence where any preliminary reduction of the ingots is made, this limited number of passes means that very heavy drafts must be taken in order to reduce the ingot to the more common bloom sizes. Third, in order to get in the greatest possible number of passes on a set of rolls, the passes must be placed one above the other, hence a groove in the middle roll must serve for both an upper and a lower pass. Fourth, the peripheral speed at the base of the grooves in any two rolls forming a pass must be equal, or nearly so, if the piece is to roll without curling when coming out of the pass. However, the pass diameter of the top roll for any pass may be a little larger than the bottom, for then the piece will be held down but may be prevented from curling down by the guards on the mill. On forty-inch mills this difference is about one-fourth of an inch and is determined by practice.

An Example of Roll Design for Three-high Blooming Mill will perhaps be the best answer to the question as to how all these conditions are met. A specific problem and a method of solving it are hereby given:

Given: Ingot 21″ x 23″, Bloom 9″ x 10″, number passes 9, Size of Mill 42″.

Required: To design rolls for the mill.

Solution:—First: The draught on each pass is found. In finding the draughts it is to be borne in mind that the draughts on the bottom passes, being edging passes, should be heavier than on the top passes; that it is well to take the heaviest draughts on the first bottom passes while the steel is hot and the piece is short, which will prevent great strains on the engine as the momentum of the fly wheel will carry across a short length; that the top passes are best made of equal draughts; and that little work can be done on the finishing pass. The reduction in size of the ingot to the bloom calls for twelve inches on one side and thirteen inches on the other, or a total of twenty-five inches. Since the reductions on the bottom passes are to be greater than those on the top, let this total draught be apportioned to give ten inches on top passes and fifteen inches on bottom ones. The draught on each top pass will then be two and one-half inches. The draught on the bottom passes may be arbitrarily apportioned, but to accord with the cautions stated above, they are determined by trial, and to give the total reduction of fifteen inches they should, apparently, be apportioned as follows: No. 1 pass, 3½″; No. 3 pass, 3¾″; No. 5 pass, 3½″; No. 7 pass,

3¼″; No. 9 pass, 1″. The complete plan for working the ingot down to size would then be as follows:

Size of the original ingot, 21″ x 23″.

No. 1 Pass, bottom, draught 3½″; size of bloom produced, 21″ x 19½″.

No. 2 " top " 2½″; " " " " 21″ x 17″.
Piece edged.

No. 3 Pass, bottom, draught 3¾″; size of bloom produced, 17¼″ x 17″.

No. 4 " top, " 2½″; " " " " 14¾″ x 17″.
Piece edged.

No. 5 Pass, bottom, draught 3½″; size of bloom produced, 14¾″ x 13½″.

No. 6 " top, " 2½″; " " " " 14¾″ x 11″.
Piece edged.

No. 7 Pass, bottom, draught 3¼″; size of bloom produced, 11½″ x 11″.

No. 8 " top, " 2½″; " " " " 9″ x 11″.
Piece edged.

No. 9 Pass, bottom, draught 1″; size of bloom produced, 9″ x 10″.

Second: The most suitable pitches for the rolls are determined. By pitch is meant the distance from center to center of a pair of rolls without clearance, or the distance between any two of the pitch lines. These are based on the size of the mill; the average pitch for the top and bottom sets of passes are equal to its size, and should be such, for reasons already noted, that each roll will be approximately one-fourth inch less in diameter than the one above it. The pitch is, therefore, determined by trial as follows: In this case the proper figures appear to be

40⅞″ from center to center of top and middle roll.

43⅛″ " " " " " bottom and middle roll.

(84″÷2=42″=the size of the mill.)

From these figures the working diameter of the passes are found as follows:

43⅛″ pitch of bottom and middle roll.

19½″ height of first pass, (See size of bloom for No. 1 pass.)

2 | 23⅝″ pass diameter of first pass.

11 13/16″—1/16″=11¾″ first pass radius of bottom roll, or first pass working diameter=23½″.

11 13/16″+1/16″=11⅞″ first pass radius of middle roll, or first pass working diameter=23¾″.

11⅞″+17″ (size of No. 2 pass)=28⅞″.

40⅞″ (pitch of top and middle roll)—28⅞″=12″, first pass radius of the top roll; or first pass working diameter of top roll=2″x12″=24″.

As this diameter is a little larger (¼″) than that for the middle roll, the pitches assigned above are assumed to be the proper ones.

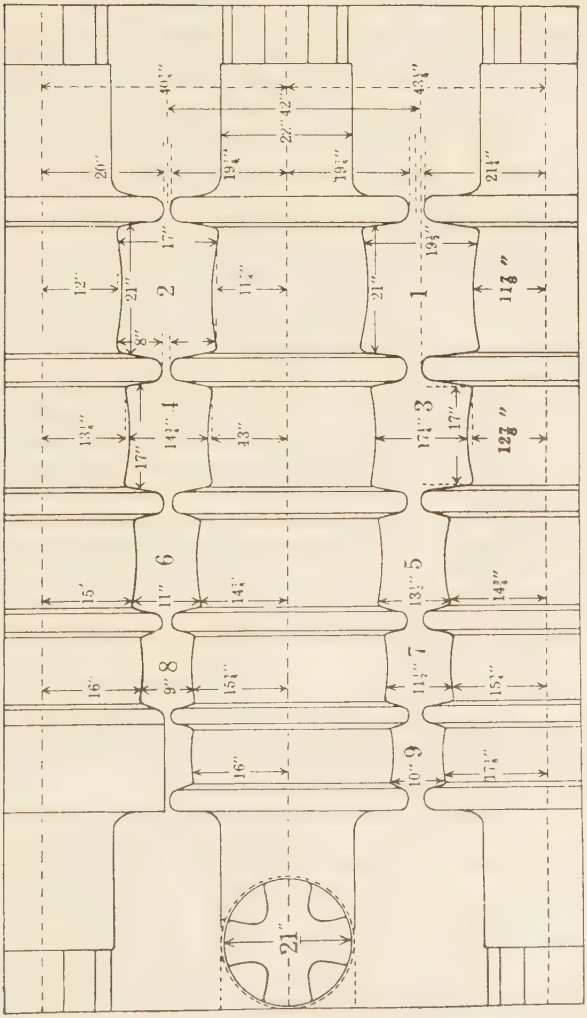


FIG. 133. Roll Design for 42″ Three-High Mill.

Third: The size of each roll is determined. As a preliminary step to finding the size of the rolls, the diameters of the middle and bottom rolls may be assumed to be the same as their pitches, forty-three and one-eighth inches. The pitch size for the middle and top roll is forty and seven-eighths inches, and if from twice this pitch the diameter of the middle roll is subtracted, the pitch diameter of the top roll is the result, which in this case would be thirty-five and five-eighths inches. If, now, the diameter of the working pass in the middle roll is subtracted from this diameter of the roll, the result is twice the depth of the groove.

$43\frac{1}{8}''-23\frac{3}{4}''=19\frac{3}{8}''$. $19\frac{3}{8}''\div 2=9\frac{11}{16}''$ depth of first groove in middle roll. Similarly, $38\frac{5}{8}''-24''=14\frac{5}{8}''$. $14\frac{5}{8}''\div 2=7\frac{5}{16}''$, depth of groove for the top roll. The sum of these two quantities is seventeen inches which checks with the size of the second pass. But more of the piece lies in the middle than in the top roll, so in order to get the same height of collar, eight and one-half inches in each roll, it is necessary to increase the radius of the top roll and decrease the radius of the middle by nineteen-sixteenths inches, making their respective diameters forty-one inches and forty and three-fourths inches. The diameter of the bottom roll would then be forty-five and one-half inches ($2 \times 43\frac{1}{8}''-40\frac{3}{4}''$). In order to get the proper clearance between the rolls, which is assumed to be one inch, these diameters are further reduced to forty inches, the diameter of top roll; thirty-nine and three-fourths inches, the diameter of middle roll; and forty-four and one-half inches, the diameter of bottom roll. These diameters give a much deeper groove in the bottom roll than in the middle, which can be overcome by cutting down the collars on the bottom roll, which has the effect merely of increasing the clearance. So to balance up the depths of these grooves a clearance of two inches is allowed between these rolls, making the final diameter of the bottom roll forty-two and one-half inches. The finding of the depth of the remaining grooves is a simple matter. Thus, for example, No. 4 pass is $14\frac{3}{4}''$ x 17". From the depth of the pass, fourteen and three-fourths inches, the clearance of one inch is subtracted, leaving thirteen and three-fourths inches. This depth is equally divided between the top and middle rolls, making six and seven-eighths inches in each. It follows that the groove in the middle roll for No. 3 pass must be the same. As the depth of this pass is seventeen and one-fourth inches, the groove in the bottom roll must be eight and three-eighths inches, ($17\frac{1}{4}''-6\frac{7}{8}''-2''=8\frac{3}{8}''$). The accompanying sketch shows a set of rolls designed according to the explanation given above. To take care of variations due to wear in the rolls and permit of their being dressed, thus increasing their life, the entire set is made a little over-size in diameter of body, usually about three-fourths of an inch. They are discarded when they have been dressed down to the same amount undersize.

SECTION V.

THE ROLLING OF SLABS.

The Rolling of the Slab is the first step in the rolling of plates, just as the bloom marks the first step in rolling the many shapes. Attention has already been called to the rolling of slabs on the reversing blooming mill. For rolling narrow slabs, the blooming mill meets all the requirements, but the width of the slabs rolled on these mills is limited to the maximum spread of the rolls on account of the necessity of edging the piece near the last passes. In America, therefore, slabs are rolled for the most part on the universal mill principle, in which the width of the slab is partly controlled by means of vertical rolls which work on the edges of the slab. The slabbing mills are not true universal mills, however, but double or duplex mills, made up of one stand of rolls, similar to the blooming mills but with plain instead of collared rolls, and one stand of vertical rolls near to and in front of the horizontal rolls. Each mill is driven independently, and both are reversing. By such an arrangement larger ingots may be rolled than would be possible on the reversing blooming mill. Since the piece is not edged under the horizontal rolls, ingots varying in thickness and slabs of great width may be handled. The following sizes as to thickness and widths of ingots are rolled by the thirty-two inch mill to be described later, namely, $23\frac{5}{8}'' \times 23\frac{5}{8}''$; $26'' \times 40''$, $26'' \times 45''$, $26'' \times 48''$; $26'' \times 53''$ and $27'' \times 57''$. The thickness of the ingot is limited by the maximum height to which the top horizontal roll may be lifted, while the width is controlled by the spread of the vertical rolls. In preparation for the rolling, the ingots are treated in soaking pits in the same manner as that already described for the blooming mills.

The Thirty-two-Inch Mill at Homestead as an Example of a Slabbing Mill: This mill is an old mill and was originally designed to roll armor plate. It is, therefore, somewhat larger and stronger than some more recently constructed slabbing mills. However, the main features and the principles of both the construction and operation are the same on this mill as those of other slabbing mills. As noted above, the mill consists of two separately driven stands of rolls—the horizontal and vertical stands,—which are best described separately.

The Horizontal Mill: The rolls on this stand are four in number, arranged one above the other on the plan of a four-high mill. Only the two intermediate rolls actually come in contact with the ingot, however, the topmost and bottommost rolls being used as reinforcing or stiffening rolls to the two intermediate ones. All these rolls are nine feet two inches long in the body, but the reenforcing rolls are thirty-two inches in diameter, while the intermediate ones are twenty-six inches in diameter. This arrangement permits a more rapid reduction of the ingot and with less

power than would be possible with only two rolls, which would have to be of large diameters to give the great strength required. The smaller roll, exposing little surface to the steel, sinks into the metal with less pressure and is turned with less power. The four rolls are held in place by a cast steel housing. The necks of the bottom reenforcing roll rest on bearings fitted into the bottom of the housing; this roll then supports the lower intermediate roll, the contact being made the entire length of their bodies. Lateral displacement of this lower intermediate roll is prevented by babbitted side bearing boxes at either end. The two upper rolls are held in two steel frames, one at each end, each of which is fitted with a brass top bearing for the reenforcing roll and a box fitted with bottom and side bearings for the top intermediate roll. As these frames move up and down with the adjustment of the top rolls, guide bars bolted to the outer edges of the windows are provided to hold them in place, while liners inserted between the frames and the sides of the windows prevent the wearing away of the housings. The ends of two plunger rods rest against the bottom of this frame while the rods extend to hydraulic cylinders which, located beneath the mill and acting under a pressure of 600 lbs. per sq. in., are used for raising the top rolls. The rolls are lowered by means of screws similar to those in the blooming mill, but in this case the power for the screw down is obtained from a 60 h. p. motor mounted on a platform a little above the top of the housing. The screws rest on breaker blocks which serve as a safety to prevent the breaking of the rolls. The maximum lift of the mill is nearly forty inches. For indicating the distance between the rolls a gauge pole and disc are provided. The disc is mounted on top of one of the screws with the marking pole adjacent to it. The circumference of the disc is divided into 100 equal parts, while the pole is divided into spaces of one inch each. These divisions on pole and disc are plainly marked and permit the opening of the mill to be read to within 1-100 of an inch. **The Drive** for the horizontal mill is connected to the intermediate rolls, the reenforcing rolls being friction driven. The motive power is furnished by a 40″ x 54″ horizontal reversing engine, which is indirectly connected to the leading or driving spindle of the mill.

The Vertical Mill is located about ten feet in front of the horizontal mill, measuring from center to center of the rolls. Like the horizontal mill the vertical mill has four rolls, two of which are reenforcing; but these rolls are much smaller than the horizontal ones, being only eighteen inches in diameter and about forty-four inches in length, or a little longer than the lift of the horizontal mill. The rolls are supported vertically in the housings by means of bearing boxes at both the tops and bottoms. These boxes are held in place by heavy rest bars which extend across the mill at top and bottom and from housing to housing, between the windows of which they are securely fastened. For adjusting the spread of the rolls inwardly two screws, acting horizontally through the sides of the housings instead of through the top as for horizontal rolls, are provided. They bear on a

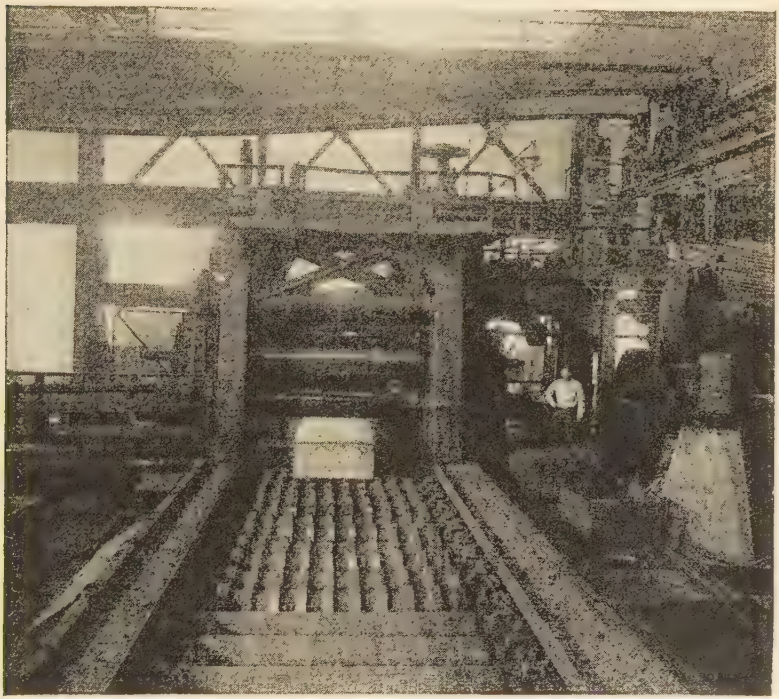


FIG. 134. View of Slabbing Mill in Operation. From the Delivery Side.

frame that extends from the top to the bottom bearings, and are operated by a 50 h. p. motor through a system of gears. For spreading the rolls apart hydraulic jacks are used. In operating the mill, all four of the rolls are driven. Starting with the engine, the connections are made as follows: The engine, a 36″ x 57″ horizontal reversing steam engine, is mounted upon a concrete foundation a little above the level of the bottom of the housings and on the opposite side of the mill from that on which the engine for the horizontal rolls is placed. The power is indirectly transmitted through two gears, one above the other, to the driving shaft, which extends from the upper gear to the farther side of the mill. To this shaft, the two outside rolls are connected by means of beveled crown and sleeve gears, while a second set of gears connecting the inside and outside rolls in pairs furnish the means by which the driving of the inside rolls is effected. The horizontal rolls are run at full speed, while the speed of the vertical rolls is controlled by the engineer to suit that of the horizontal mill. While the maximum spread of the vertical rolls is about sixty-five inches, the widest slabs rolled are only fifty-four inches wide, because this is the greatest

width the mill shears are built to cut. The excessive length of the horizontal rolls (one hundred ten inches in the body, as previously given) is explained by the fact that this mill was formerly used for rolling armor plate.

Precautions to be Observed in Rolling Slabs: The essential part of the rolling is the determination of the draughts to be taken on each pass through the mill. This determination is made by the roller from the dimensions of the ingot to be rolled, the slabs desired as given on the rolling order sheets, the temperature of the ingot as it comes to the rolls and the steam pressure available for the engines. The temperature controls the draught in that the hotter the steel the less the pull on the mill and the greater is the possible draught. Uniform temperature throughout the ingot is also necessary to insure good rolling, as steel hotter on one side than on the other causes curling of the slabs, due to the fact that steel always curls towards the cold side, because the elongation is less on that side. To assist in rolling, ingots are fed to the rolls with the hot side up and the small end first, thus affording a better grip by the rolls and preventing or lessening the tendency for the slab to curl up when leaving the mill, as they do when the cold side is turned up. Slabs are often hotter on one edge than the other, which condition also causes lateral curling, due to the greater spreading or flowing of the steel on the hot edge. Indirectly, the chemical composition of the ingot regulates the possible draught; high carbon steel, for example, cannot be heated as hot as common plate steel, hence longer time and smaller draughts must be taken in the rolling. The total vertical draught, which in all cases, except 27″ x 57″ ingots, amounts to about one inch, is taken during the first few passes. From then on, the vertical rolls are kept in contact with the steel at a pressure only sufficient to prevent tearing of the edges which results when no pressure is applied on the sides of the slab. With small ingots tearing of the steel is also caused when the ingots are not hot enough for good rolling but still capable of being passed through the rolls. In the case of large ingots that are cold, there is little danger of injuring them, because there is not sufficient power to roll them, as in the case of smaller ingots. Correct lining of the rolls is necessary to make good slabs, since if the rolls are crossed or are higher on one end than on the other the slabs curl. At the thirty-two-inch mill the driving end of the rolls is always kept slightly higher than the other end to allow for the more rapid wearing of the bearings due to the extra weight on that side of the mill. Above ⅛ inch the slabs will curl in passing through the mill. The maximum draught, i. e., reduction in sectional area, that can be taken by the horizontal rolls with the steel at a good rolling temperature is approximately thirty square inches on the entering pass and forty square inches on the return pass. The difference in reduction possible on the entering and return passes is due to the fact that, on the return pass, the vertical rolls aid in pulling the slab through the mill, while they cannot effect any power by pushing the slab when going in the opposite direction.

For the entering pass, thirty divided by the ingot width gives the approximate draught, or bite, and forty divided by the ingot width, the return pass bite. The last pass taken is entering, and is a pass in which very little pressure is used, in order to straighten the slab, roll down the top ends, and remove the convex surface due to the spring from the rolls.

Removal of Scale: During the rolling of an ingot the scale must be removed from the surface to prevent the slab, and resulting plates, from being pitted. The process employed in removing the scale depends upon the kind of steel being rolled. For removing scale on low carbon steel salt and water, the latter being sprayed on the slab at high pressure and the former thrown on with scoops, are very effective. In case of high carbon steel the scale sticks more firmly to the slab, and burlap sacks are used, as necessary, in addition to salt and water. When nickel steel is rolled, coal is used in place of salt, and burlap is also thrown under the rolls. Brush or green twigs are often employed to serve the same purpose as burlap. The actions of all these substances are somewhat similar. In each case the substance is drawn under the rolls, which tend to bring it rapidly into close contact with the hot metal. The material thus caught by the rolls is gassified by the heat, and, in an effort to escape, the gases get beneath the scale and carry it off with them. Coal and burlap, being less volatile than salt or water, are carried a little farther beneath the rolls and give a more violent action. Nickel scale is the most difficult of all to remove, and if the first scale is melted off in the soaking pits and a second formed, it is almost impossible to clean it off. All nickel bearing slabs are cleaned first on one side, then turned over by cranes and cleaned on the other side.

Shearing Slabs at the Thirty-two-Inch Mill: From the rolls the slabs pass by means of motor driven roll tables to a hydraulic shear. Two plungers are used to operate the knife, a small one on top for lifting the blade and a large one on the bottom for pulling the knife down against the steel, thus effecting the cutting. Two Wilson and Snyder pumps, an accumulator and steam intensifiers comprise the operating equipment. The slabs are cut to length by means of a scale of marks placed on a steel slab in front and to one side of the shears. Graduations on this marker indicate the distance from the shear-blade, so by running the slab out to any certain mark the length of slab is indicated by the graduation. The roll table approaching the shear-blade is also graduated in inches of distance from the blade. By fixing the eye on any spot or mark on the slab at any distance from the knife as shown by the position on the scale and watching this mark until it is moved beneath the knife, the length of slab can be obtained. The size (total weight) of the slab is determined by the dimensions and gauge of the plate into which it is to be rolled. Since the width of the ingot limits the width of the slab, planning the size of the slab starts with the selection of an ingot of the proper size. Next, the thickness of the slab must be determined, and then the length. It is evident that very careful

work is necessary in making up the mill schedule, if the steel is to be rolled to best advantage. All this planning is done in the mill office, and the shearman is generally given the lengths into which the slabs are to be cut, though occasionally he may be ordered to cut to best advantage. The first cut made on the slab is to remove the piped end. After the discard is sheared off, a few slabs are cut, when the piece is turned around with a manipulator, the bottom crops taken off, and the remainder cut into slabs. From the rolling sheets, the shearman gets the length of slabs ordered and the amount of discard that is to be taken before slabs can be cut. Cuts are usually made up to the center of the slab before turning it around. By turning the slab the shearman can tell how much steel will remain after taking off the bottom crop and better decide as to how he shall cut the remainder. Slabs are cut as ordered if possible, and if a piece is left over that is too large, or heavy, for any slab ordered, it is marked as an "odd" cut. For example, a 5000 pound slab is ordered, and, after the first slabs have been cut, the remaining piece is 7000 pounds, or 2000 pounds over the weight desired. Were this 7000 pounds to be used on a slab calling for only 5000 pounds, 2000 pounds would be scrapped in the plate mill. This system is too expensive, so the slab is marked as an odd cut and placed on some other order. The limits as to width and thickness of slab that may be sheared on this shear are fifty-four inches and twenty inches, respectively. The percentage of discard varies from about 15 per cent. on plain steel to 35 per cent. on some special orders; the larger portion of the discard is taken from the top of the ingot on account of the segregation and piping being mostly confined to this section. All discarded steel is placed in open hearth charging buggies and shipped to the open hearth, note being taken of the special alloy steel scrap, which is kept separate from the plain steel scrap. As the slabs are cut, they are stamped with a serial number, beginning with one from the first of the year. A recorder takes down the slabs made, size, number, cut, etc., and enters it on the product side of the rolling order sheet. The weight of ingot, weight of slabs made, and weight of scrap is noted, and the information sent to the product department. From this data the practice of the mill is figured.

CHAPTER VI.

THE ROLLING OF BILLETS AND OTHER SEMI-FINISHED PRODUCTS.

SECTION I.

THE THREE-HIGH BILLET MILL.

General Features of Rolling Billets: A large percentage (over 50%) of the steel produced is rolled into material of very small section. In order to finish their product in one heat, the mills rolling such sections must start with small billets. While many blooming mills of the reversing type are able to roll billets as small as 4″ x 4″ or less, which is a size much too large for the majority of the smaller mills, the inadvisability of employing these large mills for rolling billets is at once evident, and accounts for the existence of the billet mill. In order to reduce the cost of the billet, the billet mill will be placed just after the blooming mill so as to effect the reduction from ingot to billet on the original heat of the former. As to the kinds of mills used for rolling billets, almost any mill of medium size may be adapted to the work. Since the section is a very simple one and so little in the way of accuracy as to form of section or of finish is necessary, about the only requirements of the billet mill is that it be heavy enough to handle fairly large blooms and speedy enough to reduce the piece to the desired size before it becomes too cold. For the larger sized billets, a single stand of three-high rolls placed after the bloomer serves very well, but for small billets that are not intended for certain special purposes, like forgings, for example, the continuous mill is the best mill for the purpose.

Example of Three-high Billet Mill—The Twenty-eight-Inch Mill at Duquesne: As an example of the former type of mill the twenty-eight inch mill at Duquesne will be described, because every device is employed to increase the out-put, and it also is an example of how the mills are compelled to adapt themselves to change in conditions. This mill was originally designed as a rougher for a rail mill, but was rebuilt in 1907. The mill is fed by a thirty-eight-inch two-high bloomer which reduces an 18½″ x 20½″ ingot to a 7¼″ x 8½″ bloom. The twenty-eight-inch mill at Clairton placed after the forty-inch bloomer is very similar to the Duquesne twenty-eight-inch mill.

Engine: The mill is direct driven by a Cooper Corlise tandem compound horizontal condensing engine, 44″ x 74″ x 54″, designed to develop 2500 h. p. at 75 r. p. m. and 25 per cent. cut-off and to run at 80 r. p. m.

at 120 to 125 pounds steam pressure. The engine is capable of developing 4500 to 5000 h. p. The ordinary speed is about 62 r. p. m. and the normal load about 1200 h. p., the maximum being about 3500 i. h. p. per pass. The steam consumption is about 300 pounds per ton of steel rolled. The exhaust from the low pressure cylinder is taken to a central condensing plant near the engine house; this plant is of the Weiss barometric type and is equipped with the following apparatus: One 20″ x 42″ x 24″ air pump and two Wilson-Snyder 18″ x 30″ x 26″ x 36″ 8,000,000 gallon duplex compound-plunger water pumps. The engine is controlled in the engine house by a sixteen-inch throttle valve and may be shut down quickly in an emergency by a sixteen-inch quick-closing valve just above the throttle.

Drive: The crank shaft is connected through a flexible coupling to the spindle shaft. The cast steel coupling, five feet six inches in diameter, is keyed tight to the crank shaft of the engine with a bronze half thrust collar over the half coupling; a .80 per cent. carbon steel wearing plate is screwed to the outboard bearing support of the engine and separates the collar from it. Eight two and three-fourths-inch bolts hold a second half coupling to the first one. The former fits over a cast steel hub keyed to the engine end of a cast steel spindle shaft, twenty inches in diameter. The engine end of the spindle shaft is slightly curved to promote flexibility. The spindle shaft is seventeen feet eight and one-half inches long and twenty inches in diameter, and three feet seven and one-half inches from its end is the center line of a 20″ x 48″ ring oil bearing, which supports the mill end of the spindle shaft. The oil bearing is held in a cast iron yoke and base, mounted on a cast iron hot plate. The bearing is lined with babbitt and is provided with small oil grooves for lubricating. A tight crab, four feet in diameter, of cast steel is keyed to the mill end of the spindle shaft; two and one-half-inch bolts hold a four-foot cast steel loose crab to the tight crab. A cast steel compound coupling fits over the mill end of the loose crab and the adjacent wobbler of the leading spindle. The cast steel leading spindle is three feet ten and one-half inches long and sixteen inches in diameter. A plain cast steel coupling box joins the leading spindle to the middle of the mill, fitting over the adjacent wobblers of each.

Pinions and Their Housings: The pinion housings for the twenty-eight-inch mill are steel castings bolted to the mill shoes; the housing windows are seven feet three inches deep from the top to the sill and twenty-six inches wide; one forged steel liner one inch thick is used on each sill, and each window is faced on each side with a one-inch forged steel liner. These are all bolted to the housings. All these liners are forged steel of .40 per cent. to .50 per cent. carbon. The pinions are steel castings of the helical tooth type. They measure thirty-six inches in length of face, and have thirteen teeth with a pitch diameter of twenty-nine inches. Their diameter at the shrouds is twenty-seven inches, and the necks taper from seventeen and three-eights to seventeen inches in diameter; the wobblers

are sixteen inches in diameter. The total length of the pinions is nine feet two inches. All six pinion bearings are of the same pattern, being made of cast steel with three-fourths inch babbitt and four narrow brass plates set 90° apart. The bottom bearings rest flat on the housing sill liners, no beveling being required; the bearings are twenty-three inches wide, twenty-eight inches high, and twenty-three and one-half inches through. The cap for the pinion housings is a solid steel casting fitting over both housings; it has slots at its four corners for key bolts to hold down the pinions tightly beneath it. Steel eye bolts are set in the caps, so that they can be lifted easily. The housings are held in line also by steel separator rods on each side, top and bottom. The bottom and top pinions are driven by the middle pinion and all three are connected to their respective rolls by cast steel coupling boxes and cast steel spindles, unsupported.

Housings and Roll Bearings: The roll housings are cast steel, closed at the top with a cast steel cap; the housings are bolted to cast iron mill shoes. The windows of the housings are nine feet two inches deep and two feet nine inches wide. Three feet one and one-fourth inches above the sill is a ledge on which rests the bearing for the middle roll; this roll is held stationary, the others being adjusted to it. Bearings for this mill are as follows: Bottom roll: two steel carrier bearings with babbitt and brasses. Middle roll: same, and two rider bearings with similar babbitt and brasses. Top roll: two forged steel babbitted saddles for carrying the roll; two cast steel rider bearings with babbitt and brasses. The middle roll is held down on its ledge by three and three-quarter-inch rods, which are in turn held down by two five-inch set screws of one and three-quarter-inch pitch through the caps; the rods press on the rider bearings of the middle roll. The screws are adjusted by means of wrenches which fit over nuts at the top of the screws. The carrier bearing of the bottom roll rests on a seat which is fastened to a seven-inch screw running up from below the housing through its center; this screw turns in a charcoal iron nut shrunk in the mill housing, and is regulated by a gear and pinion connection from outside the housing. The gear is moved by a vertical rod with a slotted wheel in the top; a hand lever is used to turn this wheel, and thus the bottom roll is raised or lowered. The top roll is held up by two counterweights through steelyard rods in each housing reaching up to the top roll's carrier bearing; the roll is held down at each end by a single seven-inch screw of one inch pitch reaching through the cap to the breaker block on the rider bearing. The screw is adjusted like a bolt, with a short wrench usually turned by a crane.

Rolls: In this mill the top and bottom rolls are similar and interchangeable, while the middle roll differs in that the barrel of the roll has larger diameters than the bottom roll in those passes in which it acts as the top roll, and smaller diameters where it acts as the bottom roll when paired with the top roll. In passes Nos. 1, 3, 5 and 7 the diameters are

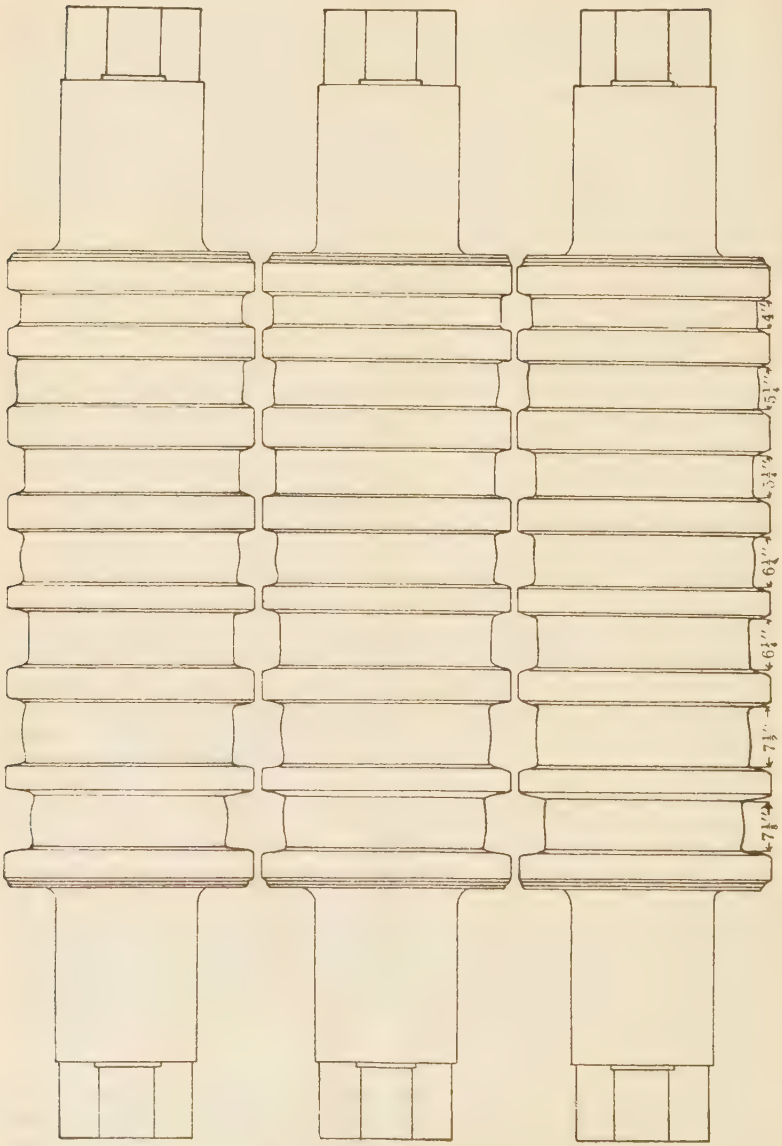


Fig. 135. Rolls for Three-High Billet or Roughing Mill.

larger in the middle roll than in the top and bottom and in Nos. 2, 4 and 6 they are smaller. The rolls are thirty and three-eighths inches in diameter, eleven feet four inches long over all and six feet four and one-half inches long in the body; the passes are shown in the accompanying sketch. One-sixteenth inch ragging is used. The rolls are made up in sets of four,—two middle rolls, one top, and one bottom roll making up the set. The rolls are changed every two weeks, when a new middle roll is inserted and the bottom and top interchanged, as only passes Nos. 1, 3, 5 and 7 have been used in the bottom roll and passes Nos. 2, 4 and 6 in the top roll; all seven passes have, of course, been used in the middle roll. At the end of a four-weeks' period, the entire set is returned to the roll shop for dressing. About five sets are kept in stock. Recently the diameter of the rolls have been increased, which permits more dressings and gives longer life. Both adamite and sand cast iron rolls are used here, as the reductions of the piece are small and no great strength is required. Adamite rolls are annealed and are very hard. The sand cast rolls are ordinary cast iron of the following composition, approximately: 1.87% total carbon, 1.22% graphitic carbon, .65% combined carbon, .37% manganese, .070% sulphur, .920% phosphorus, .70% silicon. The rolls weigh 18,000 to 19,000 pounds each. The passes are 7⅛″, 7½″, 6¼″, 6¼″, 5¼″, 5¼″ and 4″ wide. The sketch, (Fig. 135) shows the relative dimensions. When new, the rolls have a collar of thirty and three-eighths inches diameter, and three-fourths inch is taken off at each dressing of the cast iron rolls and one-fourth inch for the adamite rolls; the rolls are scrapped when the collars have been turned down to a diameter of twenty-eight and one-fourth inches.

Guide Cages: Two inches above the center line of the bottom roll, lugs are attached to front and rear of the roll housings to support guide cages. These cages are cast steel frames for holding up the guides used on all passes of this mill. They are bolted to the housings. The front guide cage is six feet six and three-fourths inches long, reaching almost to the face of the housing, and is about five feet high. It contains closed holes in front of all passes using the bottom roll and in front of No. 6 pass of the top roll; slots are provided in front of Nos. 2 and 4 passes. The rear guide cage is practically the same as the front but has all open slots in front of the top roll passes. Cast steel guides and side guards are bolted to these guide cages.

Tables: The bloom from the thirty-eight inch mill comes from the shear tables to the engine side of the roll table for the twenty-eight inch mill. This table, together with the rear table, is of the lifting type and is raised and lowered as a unit with the rear table. The front table contains twelve cast steel rollers, each of which has five collars for turning the billets. The size of these collars, beginning at the engine side, are: 16″ x 2″, 14″ x 12½″, 15″ x 12½″, 16″ x 12½″, and 16″ x 1½″. This arrangement allows four grooves, 9½″, 8½″, 7¼″ and 6″ from end to end. The

diameters of the rollers at these grooves are 9″, 10″, 11″ and 12″, respectively. The rollers are driven by a Crocker-Wheeler 75 h. p., 220 volt series wound D. C. Motor. There are side guards on the edges of the table, and at the front end are side guards for putting the bloom from the thirty-eight-inch mill into the proper pass and for protecting the other grooves. The table is thirty-four feet ten inches from center-line to center-line of the end rollers and is about six feet wide, inside. Coupled to the front of the table at the last groove is an extension table consisting of four dead rollers protected by side guards; it is fifteen feet long and fourteen inches wide and is used as an extension for the bar when ready for the seventh pass of the mill. Both front and rear tables are raised and lowered by means of fourteen-and twenty-one-inch plungers operated by a hydraulic cylinder; the hydraulic apparatus is located under one end of the front table and is connected to each table by bell-cranks from a main shaft attached to the cross-heads. The front table is equipped with a stationary manipulator for advancing the bars from pass to pass; it consists of four sets of three and one set of two cast steel fingers bolted to pedestals on the foundation of the mill. The fingers are set between rollers Nos. 1 and 2, 4 and 5, 7 and 8, 9 and 10, and 11 and 12, in line with the wide collars; they are flat cast steel plates mounted vertically and with their tops bent at an angle giving a 45° slope in the direction it is desired to move the piece. The fingers do not reach above the level of the pass when the table is elevated and the bars run out on the collars of the rollers; as the table sinks, the bars encounter the stationary fingers and slide down into the next groove. The rear table, as mentioned, is operated through the same shaft as the front table, but owing to the fact that it must raise the bars from the lower roll to the middle one and advance them one pass, it has to travel through an arc in rising to bring its grooves in line with the next passes. This is done by causing the table to slide toward the next pass, as it is raised, by the use of pull-over rods attached to pedestals on the proper side of the bottom of the scale pit; when lowered, the table slides back into place again. The table consists of twelve cast steel rollers, fourteen inches in diameter, and six feet wide, set three feet two inches apart, making a table thirty-seven feet long; the rollers are driven by a motor similar to the one used on the front table. Rollers Nos. 2, 3, 4, 5, 6, 8, 10, and 12 have 19″ x 4″ collars on their ends for turning the piece, which should tumble off them as it comes from the seventh pass. In addition there is a manipulator in the first groove; this consists of five forged steel fingers, two and one-fourth inches wide, mounted on rocker arms attached through a shaft to a plunger in a cylinder pivoted to a support on the floor of the scale pit. The upward motion of the table draws the fingers with it and, when the plunger stops rising in the cylinder, causes them to turn the piece and advance it for the second pass. This manipulator lies below the table when material is delivered from the bottom roll and acts only to turn bars 90° from the first pass to the second. The table is equipped with three heavy cast steel side guards between the four passes which the material uses in the bottom

roll. These reach back nine feet from the front to the table; there are also light side-guards at each end of the rollers reaching the length of the table. These tables make the operation of the mill practically automatic, and make it possible to roll four pieces at the same time.

SECTION II.

THE CONTINUOUS BILLET MILL.

General Features of the Continuous Mill: The continuous mill, using horizontal rolls only, is often called a Morgan mill after the inventor, Chas. H. Morgan. It consists (See Fig. 229, page 838) of a series of horizontal roll stands arranged one after the other, so that the piece to be rolled enters the first stand and travels in a straight line through the mill to the last stand, where it issues as a finished bar, thus making but one pass through each stand of rolls. In such a mill, where the piece is being rolled in several different stands at the same time, it is necessary that the surface speed of the different sets of rolls be so proportioned that each set will travel at a speed as much greater than the preceding one as the lengthening of the piece requires. With new rolls and perfect adjustment to produce the proper reduction, this relation of speed of the different stands is easily provided for by a system of driving gears. To care for the wearing down of the rolls, the bottom roll is made adjustable, and as a further precaution against little irregularities that can't be overcome by adjustments, each set of rolls is purposely set to run at a slightly greater speed than that required to conform to the speed of the preceding set, so as to put the piece under tension at all times. For turning the piece between passes twisting guides are employed.

Advantages and Disadvantages of Continuous Mills: High out-put and low labor costs are the two chief advantages of this type of mill. In addition, the mills roll the metal down very rapidly, thus giving less time for oxidation and permitting more working in one heat, and yet the speed of the rolls is low, so that comparatively little power is required to run them. Besides, the scrap losses are low, due to the fact that they can roll from blooms of any length, which fact makes it unnecessary to cut the bloom after leaving the bloomer, except to discard for pipe or other flaws that occasionally occur. Finally, the rolls are so short as to be almost unbreakable, and, therefore, very light rolls may be used for comparatively heavy work with entire safety. As to the disadvantages, the great number of rolls not only makes the first cost of the mill very high but adds immensely to the cost of rolls for different sections. For the same reason, much time is required for roll changes. Hence, the mill is best adapted to roll large amounts of one section continuously. It is obvious that complicated sections or those requiring great accuracy cannot be rolled on

such a mill. These characteristics of the continuous mill, however, make it particularly well suited for rolling billets, strips, such as hoop and cotton ties, rods and skelp. They are also employed as roughing rolls for the various combination mills.

Example of Continuous Billet Mill: As an example of the continuous billet mill the fourteen-inch number one mill at Duquesne has been selected, because it is fed by the forty-inch blooming mill, previously described. By this combination the ingot is rolled down to a bloom approximately 6″ x 4″ in the forty-inch mill from which it is delivered on roll tables, after the proper discard at the shears, to the continuous mill, where, without reheating, the bloom is reduced to billets ranging in size from three and one-quarter inches to one and three-eighth inches square. The mill consists of ten stands of rolls, and is set in line with the bloomer. The distance from the blooming mill shears to the first stand of rolls is eighty-four feet eight inches.

Drive: This mill is driven by gears from a line shaft from an Allis Chalmers horizontal vertical compound condensing Corliss valve steam engine, size 44″ x 78″ x 60″, with an indicated horse power of 3500. This engine is opposite the shears and is set so its driving shaft extends in a direction parallel to the mill line. The engine is designed to run at a speed of 75 r. p. m. at a steam pressure of 130 pounds. The maximum torque the engine is designed to give at the roll circumference is 450,000 inch pounds. The exhaust of this engine is taken to a central condensing plant. The line shaft is coupled to the crank-shaft of the engine as follows: A cast steel hub is forced on and held by keys to the end of the crank-shaft. A phosphor-bronze thrust collar is bolted in halves over this joint. The outer end of the hub, three feet ten inches in diameter, is bolted to a short steel hub having wobblers twenty inches in diameter on its other end. A cast iron coupling six feet ten inches long fits over this wobbler and that of a similar but longer hub at its outer end. This hub is two feet seven inches long, of cast steel, and its large end, three feet ten inches in diameter, is bolted to a short hub, twenty-one inches wide, which is keyed onto the seventeen-inch end of the line shaft. The line shaft, of forged steel, is made in two pieces, nine to thirteen inches diameter, and is seventy-two feet six and three-fourths inches long. At ten points on the line shaft, beginning at the engine end of the shaft, are mitre gears respectively 4′ 6″, 4′ 0″, 3′ 4½″, 3′ 11¼″, 5′ 2½″, 5′ 5″, 7′ 0″, 5′ 5¾″ and 7′ 11″ apart; these mesh with mitre gears keyed on crossover shafts that lead to their respective roll stands. These gears are supported by bearing stands along the line shaft. The crossover shafts drive the mill pinions, and give to each set of rolls, beginning after No. 1 stand, a higher speed than that of the one preceding, in order to take care of the increased length of the bar. The mill ends of the crossover shafts are carried in bearings supported on pedestals; the ends of the crossover shafts have cast iron half couplings keyed to them, and these are bolted to other half couplings which are connected to the

leading spindles by coupling boxes twelve and one-half inches long and twelve inches in diameter. All spindles, pinions and coupling boxes on the mill are cast steel. The pods on the spindles extend along their entire length. The spindles, top and bottom, are all of the same dimensions: two feet long, nine inches neck diameter, and nine and one-half inches body diameter. The leading spindles are cast hollow so that they will break under excessive strain before any other part of the mill, and are connected by plain coupling boxes, each twelve and one-half inches long and twelve inches in diameter, to the top pinions of the roll stands.

Pinions and Housings: The pinions are of the staggered tooth type with three pods. They are four feet eight inches in total length, fourteen and three-fourths inches wide across the face of the teeth, nine inches in diameter at the wobblers, nine and one-half inches in diameter at the necks, and fourteen and one-fourth inches in pitch diameter of the teeth, of which there are fourteen. The pinion housings are cast iron, in one piece, and are bolted to the pinion shoes, which run the length of the mill; each pair is bolted together at the top, as caps are not necessary. The windows are cast to shape to receive the pinion bearing boxes, which are bolted to them. The pinion bearing boxes are solid cast steel boxes, round in shape and with lugs on the outer ends for bolting to the housings. They are babbitted one-half inch deep; their dimensions are thirteen inches wide in the windows and eleven and three-fourths inches long. The pinions are joined to the rolls by solid spindles and coupling boxes already described.

Rolls and Housings: The roll housings are charcoal cast iron about four and one-half feet high, bolted to the cast mill shoes; the mill shoes run at right angles to the rolls through the length of the ten stands. The housings have charcoal cast iron caps, one fitting over each. The caps are notched at the four corners to receive the bolts to hold them fast to the housings, and in the center of each side is bored a five-inch hole for the phosphor-bronze housing nuts, in which turn the housing screws; the housing screws are of tool steel, twenty-four inches long, with one and one-half threads per inch. Each housing has a window three feet seven and three-fourths inches deep and thirteen inches wide, with a beveled sill at the bottom and a ledge, twenty-one and one-quarter inches above the sill, for resting the carrier bearing for the top roll. Each pair of housings is held in line at the top by means of cast iron separators. The necessary holes for set-pins and stud-bolts are drilled into the housings. The liners used are the ordinary steel plates of varying thicknesses.

Adjustment of the Rolls: The method of adjusting rolls in mills of this type is nearly always that of lining the bottom roll up or down to the top roll. A cast steel screw box, therefore, is placed on the sill of each housing and bolted to the housing; it is $16\frac{3}{4}''$ x $10''$ and is threaded with nine half-inch grooves, babbitted to prevent excessive wear. In each of

these is placed a special screw bolt, left-hand thread for the outside housing and right-hand thread for the inside housing. These bolts have short square ends on the outer ends but longer squares on the inner ends; the latter may be coupled together by a cast iron coupling. Above the screw bolts and resting on them and the screw boxes, are placed cast steel wedges fourteen inches long and eight inches wide, with nine half-inch grooves, babbitted. The threads are, of course, the same as for the screw boxes. On the wedges are rested the bottom bearings; these are steel castings. On the bottom they are provided with a wedge which fits against the screw wedge. The bearings have one inch of babbitt metal lining and two bronze bearing pieces. No top bearing is necessary for the bottom roll, as there is no upward pressure on it and it has no other piece to support, as the carrier bearing for the top roll rests on the ledge mentioned in the preceding paragraph. The breaker blocks are cast iron, the bottom ends of the set screws resting directly on them. These screws are squared off above the threads for adjustment by wrenches, and are provided with lock nuts.

Arrangement of Roll Stands and Guides: Owing to the fact that the speed of travel of the bar and hence the speed of the rolls is greater in each successive pass, the housings are placed closer and closer together as the bar is reduced to avoid danger of buckling. In order from No. 1 stand, the center lines of the rolls are at the following intervals: 10′ 0″, 9′ 0″, 8′ 0″, 7′ 0″, 6′ 6″, 6′ 0″, 5′ 6″, 5′ 6″, 5′ 6″. For the purpose of obtaining work on all sides of the bar and as the most convenient method of rolling, the bar is twisted between every other pair of rolls, and for this reason special guides have to be used. They are of cast steel made up especially for these stands, so that they will give the bar just the proper twist or keep it headed right to enter the next pair of the rolls. These guides are set usually in cast steel guide boxes bolted to rest bars that are fastened in ledges in the housings; where necessary, saddle bars are used to hold down the guides and guide boxes. All guides are wedged tightly in place with either steel or wooden wedges. The following is the arrangement of the guides on this mill: No. 1 receiving guide is a combination straight guide and crop shear bumper; all the rest of the receiving guides are straight; but the delivery guides are alternated thus: No. 1, straight; No. 2, twisting; No. 3, twisting; No. 4, straight; No. 5, twisting; No. 6, straight; No. 7, twisting; No. 8, straight; No. 9, twisting; No. 10, straight. Where the stands are far apart or the section is light, the bar is supported from below by narrow plates reaching from one delivery guide to the next receiving guide or else by light steel side guards.

The Rolls: The rolls for this mill are of the following dimensions: Total length, four feet six inches; length of barrel, sixteen inches; diameter of wobbler (3-pod), nine inches; diameter neck, ten inches; weight, 1500 to 1600 pounds.

Table 63. Data Pertaining to Rolls for a 14-Inch Continuous Billet Mill.

Stand	Composition	No. Grooves	Body Diameter Before Turning	
			Top	Bottom
1	Steel	1	13 5/8"	13 5/16"
2	"	1	13 3/4"	13 7/16"
3	"	2	13 5/8"	13 5/16"
4	Adamite	2	13 1/2"	13 3/16"
5	"	2	14 1/4"	13 3/4"
6	"	2	14 1/4"	13 7/8"
7	Chill Iron	4	13 5/8"	13 5/16"
8	"	4	13 3/4"	13 7/16"
9	"	4	14 3/8"	14"
10	"	4	14 3/8"	14 1/16"

Six inches is allowed between the centers of the grooves when only two grooves are cut, but only three and three-fourths inches is allowed in the case of four-groove rolls. Following is a table of the speed of the rolls of each successive stand and the observed delivery speed of the bar coming out of it with the engine at normal speed of 75 r. p. m.

Table 64. Speed Ratios on Fourteen-Inch Continuous Billet Mill.

Stand	Speed of Rolls— Revolutions Per Minute	Delivery Speed of Bar Feet Per Minute
1	17	46.7
2	21.4	54.5
3	24.55	67.1
4	30.9	99.2
5	36.6	126.3
6	44.6	156.
7	57.6	188.
8	68.7	242.
9	89.1	326.
10	117.9	417.

Cropping Shears: Between the receiving table to the mill and the first stand of rolls are hydraulic shears, pressure 450 lbs. per square inch; through these shears all blooms for the fourteen inch No. 1 mill pass. They are capable of cutting blooms up to 7" x 11" in size, but their usual work is on 6" x 4" blooms. They are used to cut crops from the front end of the bloom so it will enter No. 1 stand easily. When necessary they may be used for shearing off pipes and bad pieces that have escaped discard at the

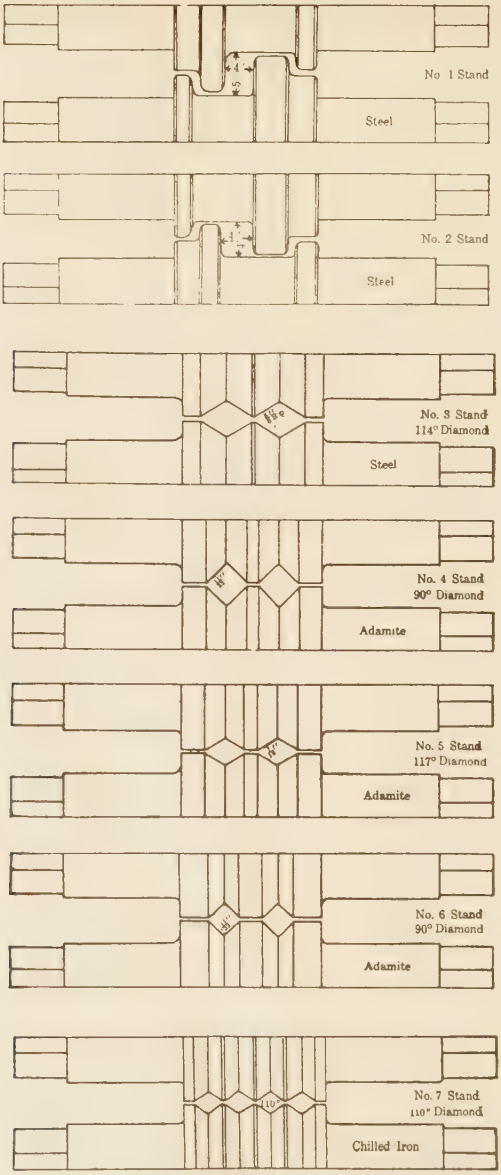
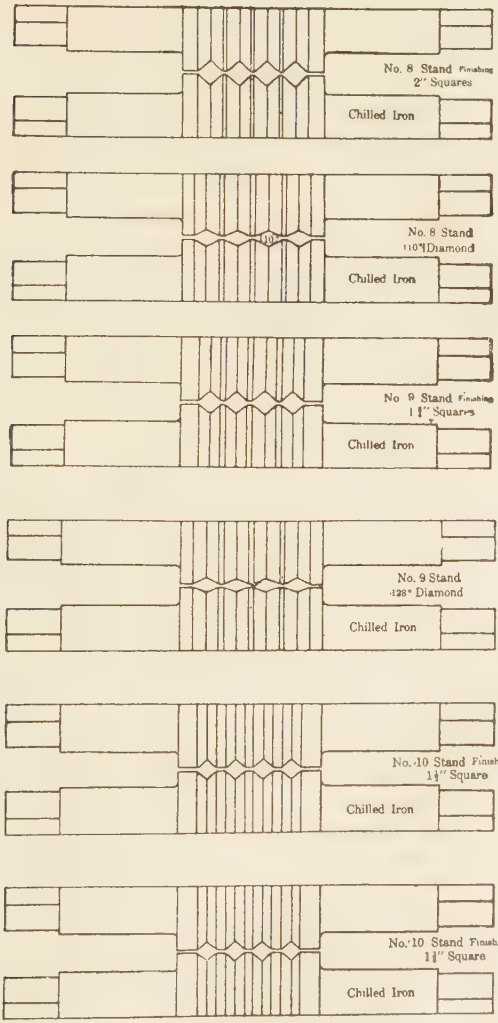


FIG. 136. Rolls and Passes for



the Continuous Billet Mill.

blooming mill shears, and for severing the bloom in case of a cobble. They are capable of a ten-inch swing from the base, and at the end of their stroke they strike the combined guide and bumper previously mentioned as the No. 1 guide. They are thrown back into position automatically, when the bloom is cut, by a heavy coil spring. The stroke of the knife blade is ten inches. The shears are vertical acting with the top blade actuated by the cylinder. No. 10 stand delivers the finished billet directly onto the receiving table for the steam flying shears; this table and its delivery table are driven through bevel gears on a single line shaft; the line shaft is driven by a jack shaft geared to a primary jack shaft which is in turn geared to the crossover shaft for No. 10 stand. As various numbers of stands are used for the various sizes of billets, the corresponding sizes of bars have a different delivery speed and the shears receiving table must, therefore, be driven proportionately, so that the billet may be cut by the flying shears without buckling and may be carried away, when cut, fast enough to keep clear of the next billet. Accordingly, various sizes of gear wheels are provided for the jack shaft to the table. The surface speed of the roll table may be set at various rates to suit the delivery speed of the billet by changing the gears on the jack shaft.

Flying Shears: The flying shears roll-table consists of eight cast steel rollers,—two, sixteen inches in diameter, on the receiving side of the shears and six, ten inches in diameter, on the delivery side. The rollers are notched with a V-shaped groove so as to hold the bar, as it comes to the shears, with one of its diagonals in the vertical, as it is in this position when it leaves the last pass of the rolls and must be sheared in the same position. The flying shears are placed with the center line of their knives twenty feet beyond the center line of No. 10 stand. The shears are actuated by a 30″ x 20″ steam cylinder. The action of the shears is speeded up or slowed down according to the delivery speed of the billet. Cutting under fifteen foot lengths is not attempted for fear of not getting the shears back to position in time to prevent buckling of the next billet. The knives on the shears have a life of from three to sixty hours; and they have to be changed for every size of billet. They have a half inch clearance above the square being cut. The horizontal stroke of the shears is ten inches.

Hot Beds: The flying shears deliver upon a table 125 feet long, from which steam operated rollers and pushers convey the bars to four hot beds extending at right angles to the tables. All of these are controlled from a pulpit in the yard. The rollers at the foot of No. 1 bed are skewed so as to bring the billets against the first pusher and make them lie parallel with it; all the other rollers are, as usual, set at right angles to the pieces. At four points on the table are hydraulically operated stoppers for stopping the bars at the hot bed desired or allowing them to pass to the horizontal scrap bed beyond the last hot bed. The hot beds are sloped up at a slight angle and are each thirty-one feet wide by fifty-three feet six inches

Fig. 137. 14″ Continuous Mill—4″ x 6″ Blooms to 2″ Billets. Drawings from Actual Sections.

long. They are built of rails, and the material is moved on each by a steam pusher connected to a cable, driven through gears by two 8″ x 10″ vertical twin simple 50 h. p. steam engines. Cold pushers are also cable connected by gears and driven by similar engines, but of the horizontal type. They convey the billets desired to the end of the bed and slide them over rail ends from the beds into railroad cars just below the hot bed level. Alligator scrap shears are provided at the end of the scrap bed, which is hand operated. The accompanying prints are intended to show the forms of the rolls, their kinds, shape of the various passes, and the different stages in the reduction of the bloom to the billet.

SECTION III.

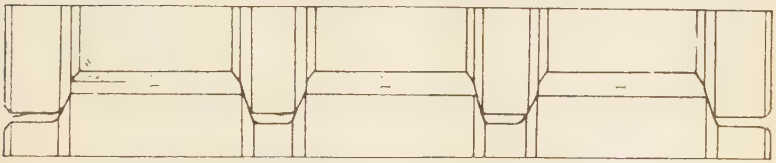
ROLLING OF SHEET BARS AND SKELP.

Difficulties and Methods of Rolling Semi-finished Flats: Sheet bar and skelp constitute the chief products that may be classed as semi-finished flats. As it is desirable to discuss the rolling of skelp in connection with the manufacture of pipe and tubes (see Part IV., Chap. IV.), the present description is confined to the rolling of sheet bar. This material may or may not be rolled from the original heat of the ingot. At Duquesne, sheet bar, as well as billets and splice bars, is rolled on the twenty-one-inch mill from the original heat of the ingot, which, being first reduced to a 8½″ x 7¼″ bloom on the thirty-eight-inch mill, is passed to the twenty-eight-inch billet mill and on to the twenty-one-inch mill without reheating. At Edgar Thomson, for example, the 9½″ x 9½″ bloom from the three-high blooming mill is reheated, when the rolling is completed on the No. 4 mill, which consists of a single train of three stands of three-high rolls, or on one of the rail mills, usually the number one. However, the method employed in reducing the material is the same, except as to details of handling, which, of course, must be changed to suit the different mills. Because the twenty-one-inch mill at Duquesne represents a distinct type of mill, this mill is selected as an example of a mill rolling sheet bar. The problem to be overcome in rolling these flats lies in the difficulty of controlling the width. In rolling blooms, billets and small slabs, the piece is held to dimensions, not only by the shape of the grooves, but also by edging the piece in certain of the passes. But in rolling sheet bar, the thinness of the piece will not permit edging, after it leaves the roughers.

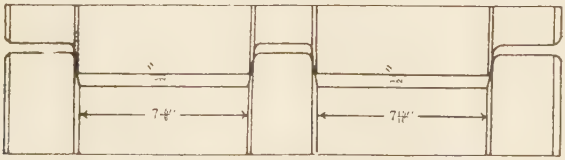
The Tongue and Groove Pass: For the purpose of controlling the width and at the same time effecting a heavy reduction in the sectional area, a form of closed box pass, called the tongue and groove pass, is used. In this form of pass a groove, corresponding in width to the width of the piece desired, is cut in one of the rolls which encloses one side and the edges of the piece in rolling, while a tongue, cut on the opposite roll, fits into the groove, thus closing the pass on the fourth side. The designing of this pass presents some very interesting features. In order to insure a proper delivery of the pieces from the rolls and provide for fitting the tongue

No 1 Stand—4" x4 Billet, Common Splice and Sheet Bar

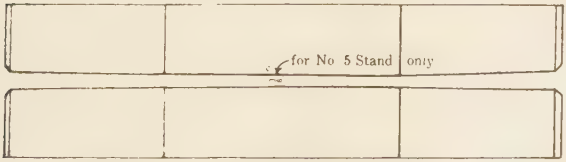
No 2 Stand for Sheet Bar



No 3 Stand for Rolling Sheet Bar



No 4 Stand for Rolling Sheet Bar



Nos. 5 and 6 Stands for Rolling Sheet Bar

Fig. 138. Roll Stands for Rolling Eight-inch Sheet Bar.

into the groove, the sides of the latter are cut at a slight angle to the bottom. Owing to the heavy drafts taken, the metal is squeezed up into the clearance between the tongue and the edges of the groove, thus forming a fin on each side of the piece, unless precautions are taken to prevent it. These fins are prevented from forming by cutting the groove with fillets at the edges, and arranging them so that the beveled edges of the piece formed by the fillets enter the succeeding pass opposite the openings formed by the clearance between the rolls. In this way no fin is formed, because the spreading of the material merely fills out the bevel of the fillet, leaving no excess metal to be squeezed up between the rolls. To enter the first tongue and groove roll the edges of the billet are well rounded off, which prevents more than a very slight fin forming in this pass. Since the piece is to be finished in plain rolls, no fillet is placed in the last tongue and groove pass. The accompanying prints show the forms of these passes, and the different steps in the reduction from the billet to sheet bar.

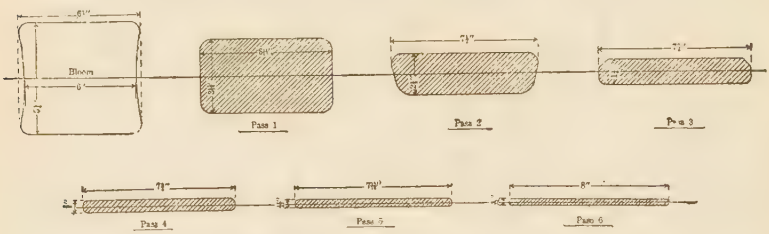


Fig. 139. Rolling Tongue and Groove for Eight-inch Sheet Bar.

Sheet Bar is all approximately eight inches wide and varies in thickness to give weights, per linear foot, from seven to forty-three pounds. The gauge in inches is found by multiplying the weight per foot by .0372 in which factor the weight of a cubic inch of steel is taken to be .28 pounds. After the mill is once set for rolling sheet bar, the different weights of bar are obtained by varying the distance between the rolls. As there is considerable difference in temperature in different billets when rolled, as at this mill, from the original heat of the ingot, it is difficult to hold the thickness constant at the finishing stand, and, in order to keep the thickness uniform, a man is stationed at this stand of rolls to adjust the screws up or down to suit the temperature of the bar. As it is necessary to produce a very smooth surface on sheet bar, on account of its being subsequently rolled into thin sheets, chilled rolls are used in the finishing stands. For the same reason, water and steam jets must be directed against both surfaces of the bar in order to remove the scale. These jets are used both at the rolls and at the saws.

Example of a Mill Rolling Sheet Bar—The Twenty-one-Inch Mill at Duquesne: As previously stated, this mill represents a distinct type. The design aims to secure the advantages of the continuous mill and eliminate the disadvantages. So, while it is practically continuous in action the different stands of rolls are placed so far apart that the piece clears one

stand before it enters the next. As a tandem arrangement alone would spread the mill out over a too great length, the various stands of rolls are usually arranged in trains that are in tandem. Such a layout requires long roll tables for carrying the piece forward and suitable apparatuses for transferring the piece transversely, such as lifting cradles, skids, diagonal roll tables, and switch, or divided, tables. In this respect the twenty-one-inch mill at Duquesne is a good example.

The Layout for This Mill, as for all mills of this type, is somewhat complicated. The mill consists of six stands of rolls arranged in two trains, separately driven and of three stands each. The two trains are separated by a distance of 119 feet. In each train the first and second stands next to the engine are three-high, while the third, on the end of the train, is two-high. For convenience the different stands are numbered in the order in which the material passes through them. Observing this order, then, stands Nos. 1, 4 and 5 compose the first train, while stands Nos. 2, 3 and 6 make up the second train. The first stand is located 105 feet beyond the twenty-eight inch mill and is provided with a receiving table fifty-three feet six inches long, equipped with switches for guiding the material from the twenty-eight-inch mill into the different passes in the first stand of the twenty-one-inch mill. These passes are three in number, all of different sizes, one of which is employed as a finishing pass for billets and the other two as working passes on material to be finished on the twenty-one-inch mill.

Arrangement of the Roll Tables: The delivery table for No 1 stand is provided with a center guard for diverting material to the billet table that leads to the 4″ x 4″ billet shears, located beyond No. 2 stand. Further along, by means of a switching device another division of the material may be made, thus sending billets either through a dummy pass in No. 2 stand to the fourteen-inch No. 2 continuous mill, located about 100 feet beyond, or to a working pass, when the material is to be finished at the twenty-one-inch mill. Since material must be cut into suitable lengths for rolling on the twenty-one-inch mill, a hydraulic shear is located 77 feet from No. 1 stand and arranged to cut on the twenty-one-inch mill half of the table only. The receiving table for the No. 2 stand begins at these shears. It is provided with a stop which may be set for lengths from twelve and one-half to thirty-eight feet. A manipulator for turning the piece is also provided in this table. The delivery table for No. 2 stand is 65 feet long and has ten rollers fifteen inches in diameter and twenty inches long; these rollers are separated by a side-guard from the rollers leading to the fourteen-inch mill No. 2. In connection with this table is a transfer skid table for moving the piece to the receiving table for No. 3 stand. It consists essentially of a frame of rails bolted together and hinged to the table, onto which they are to deliver the steel. The frame, when in its lowest position, lies below the roller tables, so that when the transfer is raised, it picks up the steel, which slides down the rail skids onto the table.

The skids are greased so that the steel will slide more easily. The frame is raised and lowered by means of links keyed to a line shaft which is in turn operated by a hydraulic cylinder. The transfer raises the bars twenty inches from the top of the delivery table No. 2 to the top of the rollers of the receiving table of No. 3 stand, the distance between the two tables being eight feet three inches. As No. 3 stand is often used as a three-high stand, this table is of the tilting type, and operated by an hydraulic cylinder placed near the stand. The delivery table of No. 3 stand is 109 feet long and serves also as a receiving table for No. 4 stand. It is stationary and, in order to receive the material when No. 3 stand is operated two-high as well as three-high, it is inclined, extending from the top of the bottom roll of No. 3 stand to the top of the middle roll in No. 4 stand. Collars on its rolls serve to turn the piece between the stands, and its side guards are adjustable so that they may be used to guide the piece into different passes on No. 4 stand. The delivery table for No. 4 stand is 79 feet long, and has guards on the side next to the engine only, in order that the piece may be transferred by means of a skid table to the receiving table for No. 5 stand. This transfer table is similar to that between No. 2 and No. 3 stands except that the piece here slides to a lower level, where it is stopped by the guards on the receiving table for No. 5 stand. Connecting No. 5 and No. 6 stands is a stationary table provided with adjustable side guards and vertical rollers for edging the piece as required.

Hot Saws and Shears: The delivery table of the last, or No. 6, stand is about 104 feet long, and at its farther end are located two electrically driven hot saws set thirty feet six inches apart. These saws, made of .80 per cent. carbon steel, are forty-two inches in diameter and one-fourth inch thick. This table feeds into a shear table, one hundred three feet nine inches long, along which are situated seven electrically operated shears. These shears are adjusted to cut at any lengths up to ninety-seven feet six inches, which is the maximum distance between the first and last shears. They may be made to cut in unison or separately, as desired. From the shear table the piece may take a straight course to the sheet bar shears and bundling cradle, or be diverted to the hot beds which are used for billets and splice bars. Returning now to the billets from No. 1 stand, it was mentioned that 4″ x 4″ billets could be diverted to a shear. This shear, of the duplex type, is located several feet beyond No. 2 stand and is provided with a bisected table of which each part leads to one of the two blades of the shears. A gauge and automatic stopper, mounted on a gauge beam about two feet above the delivery tables for the shears, can be set at one-quarter inch intervals for any lengths from twenty-three and one-half inches to twenty feet. From these shears, an elevated inclined roller conveyor carries the short billets to eight bins, each of which has a capacity of 30 tons and is located so as to empty directly into railroad cars by gravity.

Drive: Each train is direct driven by a William Tod Co. 34″ x 58″ x 60″ tandem compound horizontal condensing engine of 3500 h. p. The

usual speed of these engines is 67 r. p. m. but they can be run as high as 82 r. p. m. Both trains are direct driven through a pinion shaft from the crank-shaft of the engine. The connections between engine and mill and between the stands of rolls are made in a manner exactly similar for both trains, so that one description will suffice for both. To the end of the engine crank shaft is keyed a half coupling of cast steel, and over it is bolted a thrust collar. A second half coupling is bolted to the one next the engine. A compound coupling box—two feet two and one-half inches in diameter on the engine end and nineteen and one-half inches on the mill end and nineteen and one-half inches long for No. 1 train of rolls, and a similar box but two feet two and one-half inches in diameter on the engine end and twenty-three and one-half inches in diameter on the mill end and nineteen and one-half inches long for No. 2 train of rolls—fits over the wobbler of the second half-coupling and the mill end wobbler of the leading spindle. The leading spindle for No. 1 train is three feet four and three-fourths inches long, and twelve inches in diameter, and has three pods on the engine and four on the mill end. For No. 2 train the leading spindle is four feet one and one-half inches long, sixteen inches in diameter on the engine end, where it has three pods, and twelve inches in diameter on the mill end, which has four pods; this spindle has twelve and one-half inches near the center turned smooth to a fifteen-inch diameter for a rider bearing. A coupling box of cast steel, fifteen inches long and seventeen and one-half inches in diameter, connects the leading spindle to the center pinion of the three in the pinion housings.

Pinions and Housings: These pinions are plain steel castings, six feet three inches long, with a pitch diameter of twenty-one inches, a neck diameter of thirteen inches, a wobbler diameter of twelve inches, and a width of twenty-four inches across the face of the teeth. There are eleven teeth, of six inches pitch, cut in the helical manner. There are three pinions, set one above the other in their proper bearings in cast steel pinion housings. These housings stand about five feet eight inches above the mill floor and are bolted to the mill shoes; their windows are twenty-two and one-half inches wide and five feet eight inches deep, beveled at the bottom, and are provided with forged steel side liners, five feet four and seven-sixteenths inches long and two and three-fourths inches thick, and cast steel bottom liners, 35″ x 12″ x 2″. The housings are drilled for the necessary holes for set pins, stud bolts, cap bolts, etc. One steel cast pinion housing cap covers the housings; at its four corners are drilled four-inch holes for the cap bolts which are three feet five inches long, and are held in by a nut at the bottom and a key at the top. In the middle are fastened two hooked lifting bolts, for enabling the crane to get hold when the caps are to be removed. The bearings are all of the solid type, of cast steel, and babbitted. Coupling boxes, similar to the one connecting the leading spindle to the middle pinion, connect the three pinions to their respective spindles. The spindles are steel castings with wobblers of four pods each, extending from end to end;

they are three feet six inches long and twelve inches in diameter. They are supported on the mill end by another set of similar coupling boxes which connect them to the rolls.

Rolls and Roll Housings: The rolls on this mill are twenty-six inches long on the body for all stands except No. 3 which is thirty-six inches, because, being a three-high stand, it contains a greater number of passes than the two-high stands. The collars are usually twenty-two and one-half inches in diameter; the body diameters range from fifteen to twenty-seven inches; the diameter of the necks is thirteen inches, and of the wobblers twelve inches. The total length is six feet ten inches for the rolls on No. 3 stand and six feet for the rest. The rolls range in weight from 3800 pounds to 7000 pounds. The rolls are cut down each time they are dressed one-eighth to three-eighths of an inch until a collar diameter of nineteen inches is reached, when they are scrapped. The rolls are of the following materials for the various products rolled:

No. 1 Stand—Usually sand roll; rarely steel.

No. 2 Stand—Sand Roll for billets; steel roll for sheet bar.

No. 3 Stand—Sand Roll for billets; steel roll for sheet bar; otherwise cast iron.

No. 4 Stand—Sand Rolls always for everything.

Nos. 5 and 6 Stands—Always sand rolls except for sheet bar; sheet bar requires chilled iron rolls.

About three sets of billet rolls, about three sets of cast iron rolls for sheet bar and five sets of chilled rolls and one set of other rolls are carried on hand. The roll housings for the twenty-one-inch mill are similar for stands Nos. 1, 2, 3, and 4, which can be used as three-high, and for Nos. 5 and 6 which are only two-high. In No. 1 train, the rolls in No. 1 stand are connected by spindle and coupling boxes to those in No. 4 stand and the bottom two of No. 4 are connected to No. 5 rolls. No. 2 train is similarly connected; the top roll of Nos. 1 and 2 stands is a dummy acting as a spindle and the bottom rolls in Nos. 3 and 4 stands act the same way. The spindles, except those between No. 3 and No. 4 stands, are two feet nine inches long and twelve inches in diameter; the latter are three feet six inches long and twelve inches in diameter. The coupling boxes are all fifteen inches long and seventeen and one-half inches in diameter. The roll housings are cast iron, held in line, top and bottom, by cast iron separators. For Nos. 1, 2, 3, and 4 stands the housings stand five feet eight and one-half inches above the mill shoes and have twenty-two and one-half-inch windows; those for Nos. 5 and 6 stands rise three feet eleven and three-fourths inches above the shoes and have twenty-two and one-half-inch windows. From each housing there are two cast iron

caps, held down by square key bolts, fitting through five-inch square holes in the caps. In the center of each cap is cast a hole for receiving a phosphor-bronze housing-nut, which is pressed into the cap and threaded for receiving the housing screw. This screw, which is made of open hearth steel of .36 per cent. to .40 per cent. carbon, is five and three-eighths inches in diameter at the base and is threaded at a one-inch pitch. On all stands but No. 6, a cast steel rosette is fastened on top of the housing screws to provide means for turning them. They thus hold the top rolls tightly down. On No. 6 stand a cast steel disc is used instead of a rosette, and a long lever is attached to it, which in turn is held in place by means of bolts through slots in the outer edge of the disc. The bottom bearings for Nos. 1, 2, and 3 stands, as well as all the riders and the carrier bearings, are of cast steel. Brass bearing pieces are used in some, but not in all, of the housings. The preceding prints show how the mill may be used for rolling billets as well as sheet bar.

SECTION IV.

SOME GENERAL PRECAUTIONS TO BE OBSERVED IN ROLLING SEMI-FINISHED PRODUCTS.

Reasons for Studying Defects: A great many of the precautions necessary to observe in rolling the semi-finished products have been mentioned at various times in preceding pages. However, as failure to observe the proper precautions in rolling gives rise to defects in the material which may show up in the finished article and as the reader may be particularly interested in this phase of the business, it is thought that a list of rolling defects and their causes may be found useful and interesting. By giving the cause for each, it will be shown that many defects are unavoidable, and that even the most rigid inspection will not suffice to eliminate some defects which are a common annoyance to the manufacturer and consumer alike.

Rough Surface Due to Scale: One of the defects common to semi-finished material and one that often shows up in the finished article is a very rough or pitted surface. That this roughness most often is due to the adherence of scale on the surface of the ingot during the rolling there can be little doubt, because a careful examination of such defects will generally reveal its presence in these pits. At first thought this defect is likely to be attributed to a rolling of the scale into the surface, and the remedy at once suggested is to clean the ingot of scale during rolling. But failure to remove the scale from the ingot will not always account for this roughness. In such cases the blame for the defect is to be laid to the presence of blow holes near the surface, which in the heating of the ingot in the soaking pit become filled with molten oxides. The presence of the oxide may be attributed to two causes, namely, to the oxidation of the surface of the blow holes or to its introduction through small openings

which lead from the blow holes to the surface of the ingot. Thus, if the ingot is subject to a temperature sufficiently high to fuse the oxides, the oxide in the hole will melt, or the liquid oxide on the surface will flow through these openings to the blow holes beneath and partially or completely fill these small cavities. This oxide cannot be removed, and when the ingot is rolled, it becomes so firmly embedded in the surface that even subsequent pickling will not remove it. The only correction remaining for such defects, then, is the very expensive one of chipping or grinding. Low carbon chrome-nickel steel and some other alloy steels are very susceptible to this fault, and it is very difficult to clean the scale from its surface. While this peculiarity of nickel steel may be attributed to the same cause as that just cited for plain steels, there is much evidence to show that scale pitting in this case is partly due to an entirely different cause, namely, the reduction of the oxide of nickel by metallic iron at the rolling temperature of this steel. Thus, as fast as this alloying element is oxidized on the surface, its oxide is reduced by the free iron beneath, the result being the formation of iron oxide under the surface of the metal. This condition gives rise to an outer layer composed of metallic alloy mingled with oxide, in which the oxide acts as a binder between metal and surface scale. It can readily be seen that this layer may vary in thickness, and the merging from all metal to all oxide is gradual, resulting in what may be termed an interpenetration of metal and oxides, which causes the scale to adhere most firmly to the surface.

Cobbling: The most frequent failure in rolling is cobbling. It occurs at the blooming mill as a turn down or twisting of the piece in the rolls, at the rougher in the same way or by catching and buckling on the roll table, and at the other mills as a roll table or mill accident. The piece may catch on a table and buckle up and be prevented from coming through the rolls; it may catch against a guide and buckle; or it may buckle against the rolls, if delivered to them too fast. In such cases, practically all of the piece has to be scrapped; the uninjured sections of partially cobbled blooms can usually be finished and be made use of.

Laps: An over filling of a pass causes the steel to spread between the collars of the rolls and causes a lap; this is usually rolled down into the surface, partially or altogether, if the steel is turned for the next pass, and the place between the lap and the rest of the piece is left as a surface crack, or seam. A lap may result from a crack in the rolls into which the steel flows.

Collar Marks: Owing to overdraft or possibly defective heating, or, in the blooming mill, to too infrequent turning of the piece, the steel will overfill the groove, causing collar marks. Lack of alignment or proper adjustment of the rolls or any other incident that gives an unequal draught will cause the collars to bite into the bloom and injure it. Collaring leaves deep cuts that can seldom be rolled out, hence the injured portion of the bloom is discarded at the shears.

Guide Marks: Guides, if they are too deep, out of line, or required to do too heavy duty will score the surface of the steel, usually, in fine lines, or else may tear its edges.

Ragging Marks: Ragging leaves protrusions on the surface of the steel, and sometimes these are lapped over, showing in the finished steel in irregular seams and cracks. On mills rolling steel that is to be rolled to small section or a fine finish, only light ragging is used.

Off Size: If a bloom, slab, or billet is off size, it makes the weight of the predetermined cut different from the actual cut and will prevent an order from being accurately filled, or may even cause a deficit of steel to apply on the order. On mills of the class in question it is difficult to work to absolutely correct sizes, hence, a tolerance for weight as well as for size should be given.

Unequal Draughts: These defects are due to the rolls being out of parallel with each other, causing one side to be rolled light and the other heavy. This condition may result also in a turning down of a lap in the next pass in the case of a bloom, or a cobble in the case of a billet.

Seams: Seams may be caused by blow holes, by laps, or by tearing of the steel due to causes which will be explained in a succeeding paragraph. Slivers or scale, first rolled into the surface, and then torn out, may leave cracks that will roll down to form seams. Seams may also be caused by too much belly in the roll, or by not turning the piece often enough during the rolling of the bloom, as illustrated in Fig. 140. Seams are especially injurious in steels for forgings and for heat treatment. They seldom fail to cause the steel to crack in quenching, particularly if the steel is quenched in water.

Slivers: Slivers are due to defective teeming of the molten steel and to a tearing of the corners of the steel in blooming, roughing, or finishing. Tearing is attributed to many things, such as over oxidation in the open hearth, burning, twisting in the rolls, and improperly adjusted guides. Soft steels and high sulphur screw stock are especially subject to these defects.

Scabs: Scabs are found on steel if it is burned or if scale is rolled into it.

Shearing Defects: Failure to discard properly at the shears may result in rejection of product. Aside from this neglect, other defects may be produced by the shearing. Thus, a dull shear knife or one with too great clearance will not make a clean cut and will leave a lip on the side of the steel where its stroke ends. An unavoidable effect of shearing is to produce what may be termed a mechanical or manufactured pipe. In the shearing of billets and slabs, especially in the case of 4″ x 4″ billets and larger, it frequently occurs that the sheared end shows a pulled-out condition. There are a number of things responsible for this condition on the sheared ends. Thus, highly segregated steel will not shear uniformly and often results in a pulled-out condition, and the same thing is almost sure to happen in case the billet or bloom has a spongy center. The temperature

Fig. 140. Good and Bad Practice in Rolling Blooms.
Top bloom shows effect of not turning the bloom often enough.

at which the billets are sheared plays a very important part, also. These pulled-out cavities on the sheared end may have a depth of more than one inch. It is readily seen what happens when such billets are reheated and rolled into small sizes. The pull-out is closed up and elongated with the rolling, and when rolled into a small rod or any other smaller shape the effect of this pull-out condition may extend far back into the finished material. Very often this manufactured pipe is mistaken for a genuine metallurgical pipe, since in most cases it is centrally located. The injurious effect of a manufactured pipe on the physical properties of steel is similar to that of a metallurgical pipe.

Splits or Cracks in Billets and Blooms: In breaking down ingots it often happens that the metal does not yield properly to the draught, and the surface structure is cracked or torn at a number of places, and sometimes to a depth of two or three inches. As the rolling is continued, these torn surfaces are gradually closed, but not perfectly welded, and become much elongated, so that it is not easy to detect them in the finished article, not only because they are completely closed but because of the new scale, which, forming after the rolling is finished, totally covers up all signs of their presence. This feature makes their occurrence all the more serious, because, though their dangerous character is recognized by the manufacturer, and every attempt is made to eliminate them, the inability to detect them often leads to their passing the inspection. These cracks are attributed to many causes. In the first place, certain grades of steel, more particularly those in which the carbon content lies between .18 per cent. and .22 per cent., are more susceptible to this defect than others. The sulphur and manganese content also appears to affect the tendency of ingots to crack. Hence, many steel men are inclined to lay most of the blame to chemical composition, while others hold that the fault lies in improper treatment in manufacture. It is a fact that steel not properly made may be red short, and that the steel can be injured through too heavy draught and too much reduction without turning, or poorly designed passes in rolling, cannot be denied. It also appears that the heating of the ingot in the pits may exert an important influence upon the rolling properties of the steel.

Inspection: Blooms, billets, and slabs are inspected on the mill yard, and when defects are not very deep, they are chipped out with chipping hammers, if so ordered, before the steel is shipped. All inspection is directed to the elimination of the defects listed above, and rejection is according to the strictness of the order in respect to this requirement. Billets and sheet bars are hot bed inspected, and in addition to inspection for surface defects sheet bar is also tested for exactness of weight.

CHAPTER VII.

THE ROLLING OF THE HEAVIER FINISHED PRODUCTS—PLATES.

SECTION I.

PREPARATION OF THE STEEL FOR ROLLING FINISHED PRODUCTS.

Reheating: While a few finished steel articles, such as plates, large rails and heavy shapes, which on account of their large mass retain their heat for a considerable length of time, may be rolled by rapid methods directly from the ingot without reheating, the majority of articles are so small that their temperature would fall far below the rolling range before the great amount of reduction required could be accomplished. For all such articles a reheating of the bloom, billet, or slab is a necessary step preliminary to rolling. Needless to say, this reheating of the steel is a matter of great importance and requires even more care than the heating of ingots. Compared with hot ingots the nature of heating is very different, for here all the heat is conducted toward the center from the surfaces exposed to it; and since in practice it is well nigh impossible to expose all surfaces equally to the heating medium, uneven heating is likely to occur, the result of which is a variation in the dimensions of the finished section. Here, too, as with ingots, the danger of burning or overheating is ever present. As the temperatures attained are far above the critical range, the reheating tends to undo the refining of the previous rolling. Since the extent of this obliteration of the original structure is about in proportion to the temperature above the critical attained it is desirable to keep the reheating temperature as low as possible, and to finish the rolling as near the critical range as practicable. However, some finished materials are so light that the highest temperatures attainable without injury to the steel are barely sufficient to complete the rolling, and in addition the wear-and-tear on the mills incident to rolling at the lower temperatures increases so rapidly as to add very much to the expense of rolling. Again, the surface of the metal is oxidized very rapidly in a flame or a hot atmosphere even slightly oxidizing, and this oxidation results in the formation of an insulating coat of scale that retards the heating. This scale may cause trouble in other ways, also, because, at the temperature which it is often necessary to maintain in the furnace in order to heat the steel to the proper temperature for rolling,

it becomes pasty or quite fluid, and blooms or billets in contact in the furnace are often cemented together by it. Besides, the surface of the piece, being covered with this pasty scale, is liable to cause pieces of brick, sand, or other foreign substances to adhere to it, and these, being rolled into the steel, produce serious surface defects in the finished material, some of which are known as scabs, brick spots, pitted surfaces, etc. The loss of metal due to the formation of scale will sometimes amount to as much as 5 per cent. and is seldom under 2 per cent.

Types of Reheating Furnaces: Reheating furnaces cannot as yet be said to have reached a standard in design and construction. They are, therefore, of various forms and types, and each furnace is constructed along lines which were thought to be the best suited to the local conditions at the time of its erection. Most of these furnaces are, however, of the reverberatory type, and may be fired with coal, gas, tar or oil, though the gaseous fuels are much preferred for this purpose on account of the ease with which the temperature may be regulated. In order to conserve the heat as much as possible, they may be provided with waste heat boilers or be constructed on the regenerative or recuperative principles. New mills, however, the majority of which are being electrically driven, cannot employ the waste heat boilers. The more modern furnaces are, then, built either on the regenerative or the recuperative principle, in both of which gaseous or liquid fuels or pulverized coal are used.

The Regenerative Reheating Furnace is similar in working principle to an open hearth steel furnace. Gas and air ports at each end of the furnace are connected by flues that lead to checker chambers, made of the proper refractory materials for retaining the heat from waste gases and giving up the same to the ingoing air, or air and gas if producer gas is used, the current being reversed at certain intervals of time. Unlike the open hearth furnace, however, the checker work for these furnaces is usually placed under the furnace, and, instead of the basin-like hearth, the reheating furnace is provided with a floor practically on a level with the door sills. A low bridge wall, which separates this floor from the up-and-down takes, forms a kind of combustion chamber and prevents the flame from impinging directly upon the steel. Above this combustion chamber the roof of the furnace slopes downward toward the middle of the furnace and reverberates the heat of the flame upon the floor. The steel is charged through lifting doors in one side of the furnace, and it may be drawn either through these same doors or through doors in the opposite side. Originally, it was the general practice to line the bottom of these furnaces with refractory silicious sand, hence they are often called sand bottom furnaces. As the scale in melting unites with this sand to form a slag of a too high per cent. of silica to be used economically, these furnaces are now made up of magnesite or cinder, which, melted into place, makes it possible to use the resulting cinder in the open-hearth or blast furnace. These furnaces are used mainly

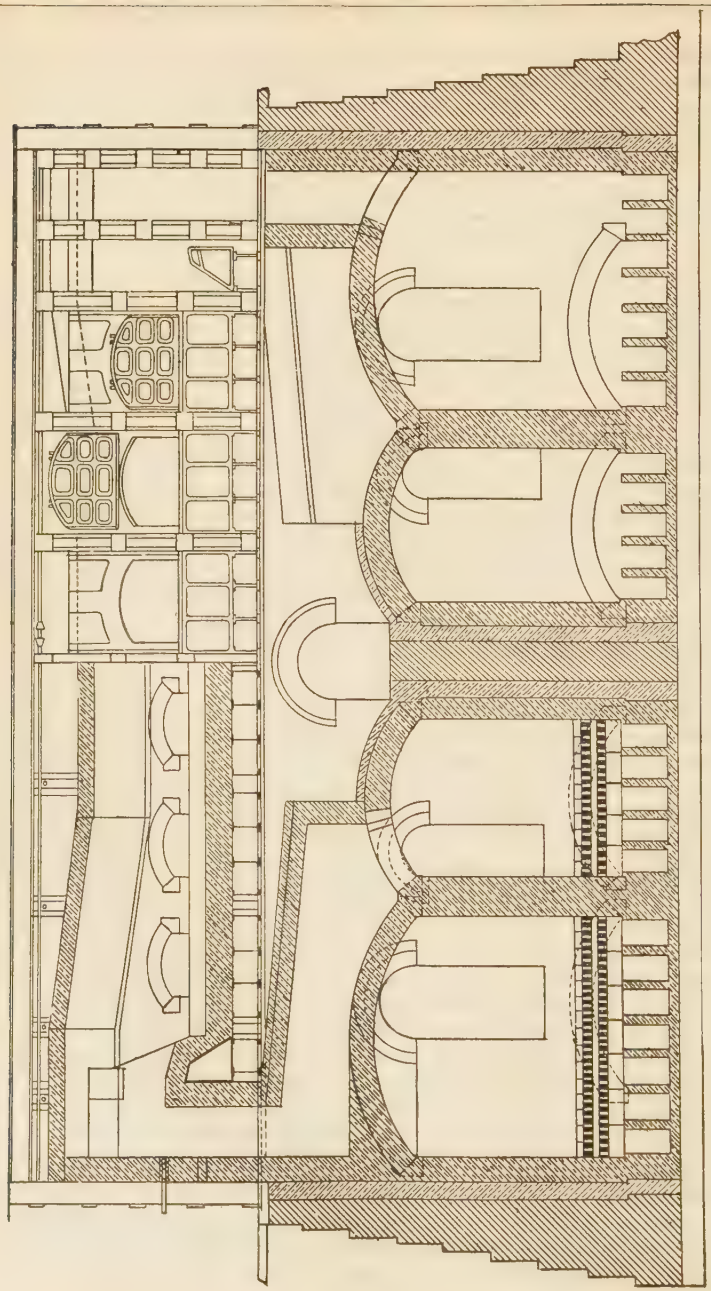


Fig. 141. Regenerative Reheating Furnace. Longitudinal Sections.

for reheating heavy material, such as blooms, slabs, and the larger billets, for which purpose they are very well adapted.

The Recuperative or "Continuous" Furnace works upon the principle of counter-currents throughout. The combustion chamber is located at one end of the furnace, where the heated steel is drawn, while the chamber for recovery of the waste heat is located at the opposite end, which is always nearest the stack and where the steel is charged. In one current, the hot gases and flame from the combustion chamber are drawn by the chimney draft over the floor, which is separated from the combustion chamber by a bridge wall, and then downward through a series of spaced iron pipes to the stack flue. In the other current, the course of the steel and the air for combustion run counter-current to the heat, the steel over the floor of the furnace, the air through the enclosed space about the hot pipes, thence through a flue under the floor to the combustion chamber. The passage of all may, therefore, be made continuous, hence the name, continuous furnace. The drawings on the next page are of a furnace designed for long billets. It will be observed that the billets move from the coldest part of the furnace to the hottest part, hence they are heated very gradually, reaching the rolling temperature just prior to drawing. The scale, therefore, does not melt, and no slag is formed in the continuous furnace if it is fired with gas, oil or tar. When powdered coal is used for fuel, the silicious ash unites with the scale to form an easily fused slag that collects at the discharge end of the furnace. In order to push the billets through the furnace suitable pushing devices must be provided, and to aid in this work the floor of the furnace is sometimes inclined, sloping downward from the charging to the drawing end. To prevent the tearing up of the floor, skids for supporting the billets are provided, built into the bottom. These skids are generally made of heavy pipe through which a stream of water flows to keep them cool. An objectionable feature in the use of the skids is that they cause cold spots in the steel where the billets rest upon them. To overcome this defect the pipes are bent or off-set at the lower ends, or the billets may be delivered from the skids to a section of the bottom lined with magnesite. In this way the temperature of the cold spots is restored to near that of the rest of the billet.

The Advantages of Continuous Reheating Furnaces are numerous. In the first place, they are the best type of furnace to precede a continuous mill. The use of complicated charging and drawing machines is avoided. The heating, being confined to one end of the furnace, makes it easy to regulate the temperature to suit the different grades of steel, and to heat to the rolling temperature only those billets that are to be used at once. Where the billets used are of constant length, the width of the furnace is so proportioned to the length of billet that the entire bottom is covered with the steel to be heated. Thus, there are no vacant areas on the bottom to decrease the heating efficiency of the furnace. The accompanying prints are intended to show the chief features in the modern construction of these two types of furnaces.

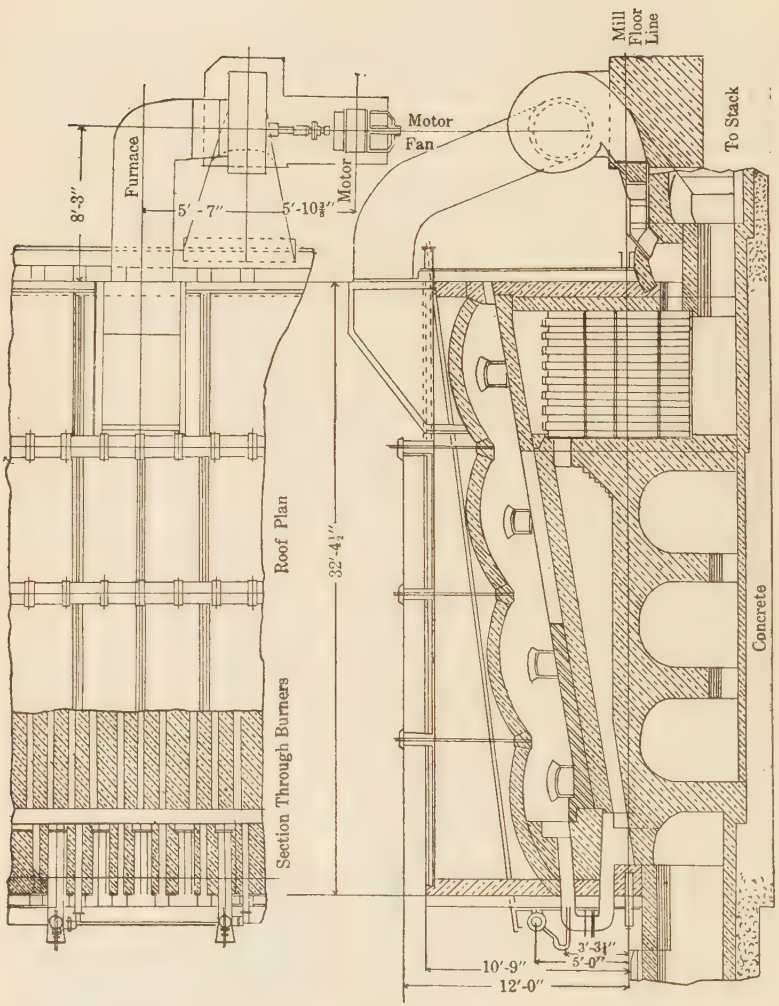


FIG. 142. Continuous Heating Furnace. Plan and Longitudinal Section through Center.

SECTION II.

THE ROLLING OF SHEARED PLATES.

Methods of Rolling Plates: As previously indicated, plates may be rolled either from ingots or from slabs, and on several different types of mills. Thus, in England, and a few places in this country, Birmingham, for example, plates are rolled on a two-high reversing mill consisting of a train of two stands of plain rolls. In these mills, the stand nearer the engine has both rolls driven and is used for roughing, while the second stand is used for finishing and has, therefore, only the bottom roll driven. In the majority of these mills the rolls are run hot, that is, no attempt is made to

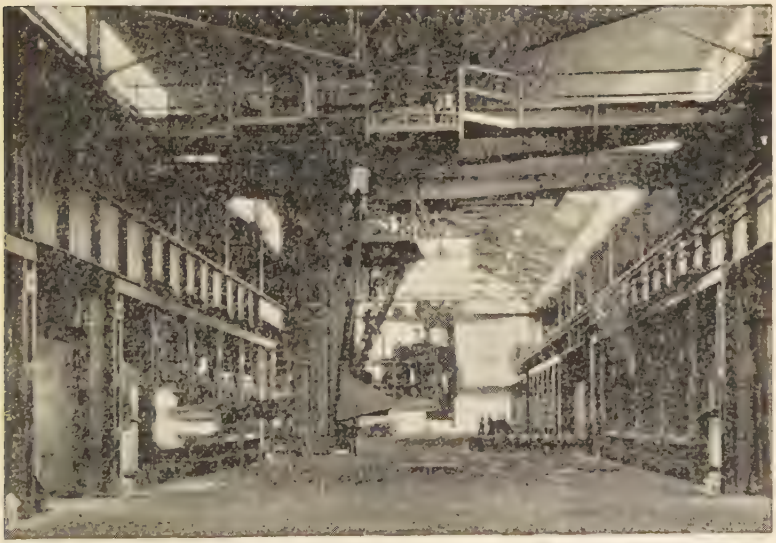


FIG. 143. Interior View of the Furnace Room of a Plate Mill. The furnaces are of the regenerative type.

cool the rolls during the rolling. In America the more common practice for rolling plates is entirely different. In all cases the rolls are kept cold by directing streams or sprays of water upon them during the rolling, and two types of mill, neither of which is like the English mills, are used. One of these, the universal mill, has already been mentioned, and will be described more in detail later, while the other, the invention of Mr. B. C. Lauth, of Pittsburgh, is a kind of three-high mill. In this mill the top and bottom rolls are driven, are of the same size, and of large diameters, while the middle roll is friction driven and, in diameter, is usually about two-thirds the size of the other two rolls. The maximum size of the middle roll is determined by the width of the housing windows, as the roll is removed by passing it endways through this opening. The top roll can be raised

and lowered in the housing, and the middle roll, through suitable levers hydraulically or electrically operated, can be brought into contact alternately with the top and bottom rolls, which then play the part of reenforcing rolls. Thus, in making the bottom pass, the plate passes between this middle roll and the bottom roll, while the top roll is used as a reenforcing roll. On the return pass, the middle roll is dropped down upon the bottom roll, and the piece, having been raised to the proper level by a tilting table, passes between the top and middle rolls. In either case, the amount of draught is controlled by screw downs acting against the top roll in a manner somewhat like that of the blooming mill. The advantage of this construction will become apparent as this study advances. Plates rolled on this mill must be sheared on all edges, hence they are called "sheared plates" to distinguish them from universal mill plates, which are sheared only on the ends to obtain the lengths required. The size of the sheared plate mill is determined by the length of the bodies of its rolls, while universal mills are distinguished by the maximum spread of the vertical rolls.

The One Hundred Forty-Inch Mill at Homestead as an Example of a Sheared Plate Mill: In this mill the top and bottom rolls, which must be carefully matched and of exactly the same diameter, are each approximately thirty-eight and three-fourths inches in diameter when new, and the middle roll twenty-two inches. All three are chilled rolls, the depth of the chill being between one and one and one-half inches. The bottom roll is held in place by bottom and side bearings of brass, which are fitted into the bottom of the cast steel housings. For the top roll, which requires both top and bottom as well as side bearings, riders for containing the brasses are provided. This roll is supported from below by steel-yard rods which extend from the bottom rider to the shorter arms of counterbalanced levers in the pits beneath the mill. In this respect as well as in the method of screwing down the top roll, the construction of the mill resembles the forty-inch mill at Duquesne. For driving the screws, however, a 60 h. p. motor is provided, instead of the hydraulic cylinder, and is connected to the screws through a worm shaft and crown gear. For indicating the draught on the mill a large drum or cylinder, about four feet in diameter and with an altitude equal to the total lift of the mill, is mounted on the top of one of the screws. The surface of this cylinder is divided vertically into parallel spaces, the width of which equals the pitch of the screws, one and one-quarter inches. The circumference of each circle separating a pair of spaces is then divided by vertical lines into a number of equal parts. By means of this arrangement and a stationary pointer, mounted on the housing beside the cylinder and set to point at zero on the drum when all the rolls are in contact and screwed down tight, the distance between the rolls may be read off direct and with great accuracy. For holding the middle roll in place, bearing boxes with side bearings which fit into chocks placed on the side of the housing windows are provided. For keeping this roll in line, liners are employed, and for raising and lowering it, a rest

bar built on the plan of a swinging lever is fitted over each neck outside of the housing and across the window. One end of each rest bar is supported at an almost constant level by means of a turn buckle rod hung from the top of the housing, while the opposite end is connected to the plunger of a hydraulic cylinder which, located in the pit beneath the housings, furnishes the power for raising and lowering the roll. In many cases this cylinder is located on top of the housings, and in the most recently constructed mills, electric motors are employed instead of the hydraulic cylinder.

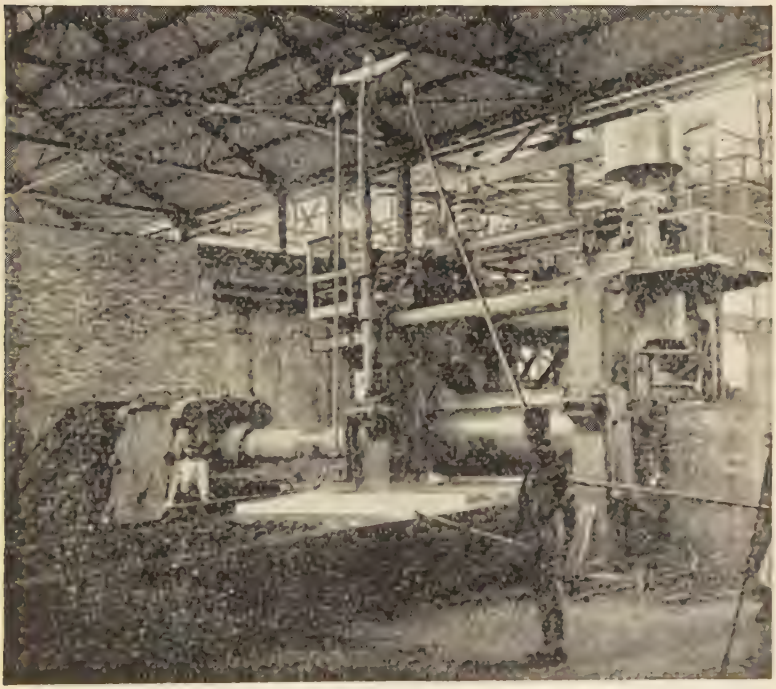


FIG. 144. View of a 110-inch Sheared Plate Mill in Operation.

The Drive and Connections: The top and bottom rolls are connected to the pinions through coupling boxes and spindles similar to those in the blooming mill. The spindles are eleven feet long, and both are supported at their centers by suitable bearings. The saddle box for the vibrating spindle is attached at one end to the pinion housing and at the other to the roll bearing box, thus keeping the motion of the saddle and spindle co-incident with that of the top roll. Since the middle roll of the mill is friction driven, the middle pinion is used as a driving pinion only, and is smaller than the top and bottom ones, the speed ratio being 11 to 10. The

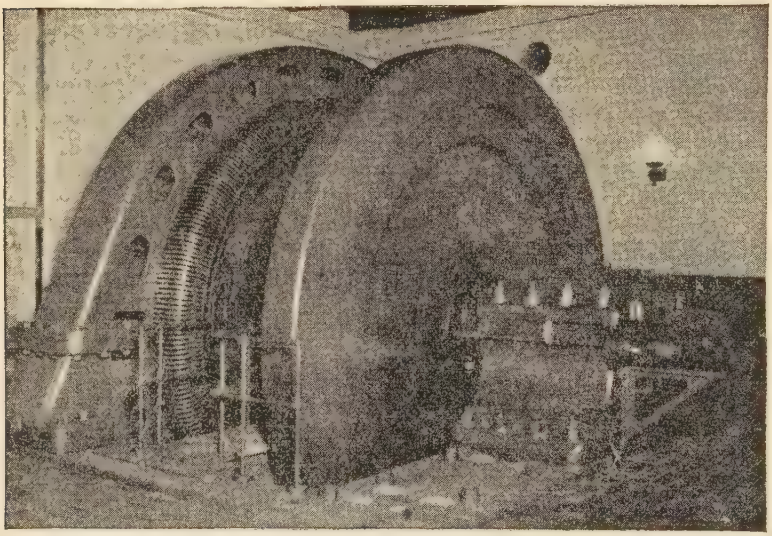


Fig. 145. The 4000 h. p. Motor Used to Drive the 110-inch Mill shown on the preceding page.

pinions are of the helical toothed type and are held in cast steel housings. A short spindle, four feet eleven inches long, connects the middle pinion to the driving shaft of the engine on which is mounted the fly wheel. This mill is driven by a 42″ x 66″ x 60″ tandem compound engine, capable of giving 3500 h. p. at the speed of 64 r. p. m. Nearly all the new mills built since 1916 are electrically driven. The new one hundred ten-inch mill at Homestead, otherwise known as the Liberty mill, is so driven. This motor was built and installed by the General Electric Co. It is designed to develop 4000 h. p. and to give a speed of 82 r. p. m. on full load. It uses alternating 3-phase current with a frequency of 25 cycles per second and a pressure of 6600 volts. The installation is marked for its simplicity; the peak loads are taken care of by means of a 55-ton fly wheel mounted on the same shaft with the motor.

Difficulties in Rolling Sheared Plates: While the rolling of plate may appear to the novice as one of the simplest of rolling operations, yet there are problems connected with the rolling of wide plate that require the combined skill and experience of the heater, the millwright, the roller, and roll designer to overcome. If the slabs are not heated uniformly in all parts, the plates will curl and buckle in rolling, while a similar effect is produced if the rolls are even slightly out of alignment. The stretch of the housings and the stoving up of the screw are minor considerations in overcoming the difficulties of rolling exactly to gauge. The wearing

away of the rolls, which in actual operation, takes place faster in the middle portions than at the ends, causes them to become hollow in a short time so that the plate is thicker in the middle than at the edges. Since the pressure for rolling must be applied at the ends of the rolls, this effect is increased by the bending of the rolls. The opposite effect would be produced if the rolls should become hot in the middle, the expansion causing an increase in their diameters. This last complication is avoided by keeping the rolls cold with water sprays above them. This water, running down upon the plate, has a tendency to cool it faster, but this cooling is not as rapid as might be expected, because the water assumes the spheroidal state on striking the very hot plate and glides off without being vaporized to any great extent. At the one hundred forty-inch mill, the spring and wear in the rolls are provided for in the following manner: To remove the effects of wear, the top and bottom rolls are dressed down every Saturday, either in position by attaching an electrically driven reduction gear to the driving pinion, which virtually converts the mill into a lathe, or by removing them and sending them to be lathe turned in the machine shop. To neutralize the spring in the rolls, the middle roll is turned so that its diameter at the middle is a little greater than that at the ends. If this swell or belly in the roll were made to fit the top and bottom rolls, it would almost represent an arc of a very large circle, but as it is impossible to dress the roll in this way, the lines are cut only approximately correct by tapering the ends and leaving the central portion of the roll cylindrical in form. The amount of the taper will vary with the hollowness of the mill, but is never less than one-sixty-fourth nor greater than three-sixty-fourths of an inch, thus making the difference in diameter between the ends and the center vary from one-thirty-second to three-thirty-seconds of an inch. The distance from the end of the roll to which the taper extends may vary from forty-six to fifty-six inches, thus making the central cylindrical portion twenty-eight to forty-eight inches long, and depends upon the width of plate being rolled. It is the practice, when advantageous, to roll the wide plates at the beginning of the week, while the "mill is full," that is, before the rolls have been hollowed out by wear, and to roll the narrower plates at the end of the week when the rolls have been worn down, and the hollowness of the mill is more pronounced. Even with these changes the mill will often become so hollow that it is necessary to roll the edges a little below gauge in order to get the weight correct. Hollowness in the mill tends to make the edges of the plate dovetail or buckle. During the week the middle roll will be changed four to six times.

The Rolling Process on this mill, as on the English mill, may be looked upon as being performed in two steps or stages, namely, a roughing or breaking down stage and a finishing stage. In the breaking down of the slab the most important feature of the rolling is the determination of the draughts, the size of slab and the spring of the rolls being the controlling factors in this regard. With a heavy slab, that is, one six to ten inches

thick, a maximum draft, or bite, of about three-fourths inch is possible. The amount of bite decreases as the slab thickness decreases and the width increases. The greater the surface the less the possible draught on account of the greater amount of work necessary in rolling. Following the first few passes the draughts become smaller and smaller because of the increased work required and also to allow material for the finishing. At least one-fourth inch is allowed for the finishing passes, as this amount is required to give sufficient material with which to remove the effect produced by the spring of the rolls. Were the spring not removed, that is if the plates were finished by a continuance of passes carrying the heavy draughts, the middle of the resulting plates would be much heavier than the sides. By decreasing the draughts the "spring" is removed, and the plate approaches nearer the desired weight and gauge. Blind passes, that is, passes in which no additional pressure is applied to the rolls, are also used in finishing for the same reason. The heavier gauge plates cause less spring in the roll, and fewer finishing passes are necessary, while with light gauge plates, especially on a full mill, it is necessary to start the finishing when about one-half inch above the final gauge, since a bigger draught is necessary to hold the plate and prevent buckling. Near the beginning of the rolling, the slabs are passed through the mill transversely a few times to obtain the desired width and are then rolled longitudinally. In gauging the width six inches are allowed for shrinkage, shearing, etc., on plate not over eighty-five inches wide, while seven to eight inches are allowed on plate from ninety inches to the maximum of a hundred thirty-two inches. Extra allowance on the wide plates is necessary to take care of the overlap, or lamination, of the top and bottom sides due to the greater flowing of the metal on these faces during rolling. Any large variation in the distance between the rolls from end to end shows up in the plate at once, since under such conditions it will curve to the side on which there is the less draught. If the variation is small it may not show up in this way. The plates are gauged four times daily at the edges and in the middle to determine the hollowness and variation. Excessive hollowness is corrected by putting in a new middle roll, while variations are overcome by inserting or removing liners under the bearing boxes. During the rolling, scale is removed with salt on common steels or with burlap and coal on nickel steel, as in the rolling of slabs.

Cooling and Straightening: In order to keep the cooling of plate uniform, the roll tables are preferably provided with collared, or disc rolls instead of plain ones, which cause black streaks to appear across the plate. Disc rollers in the tilting tables of the mill also make it possible to roll very narrow slabs. These slabs are difficult to handle on plain rolls, because they do not ride these rolls in a horizontal position, but tend to fall down between them edgewise. This difficulty is overcome with the disc rollers, for by alternating the discs the bearing surface from roll to roll is brought nearer together than is possible with plain rolls, and there is no straight

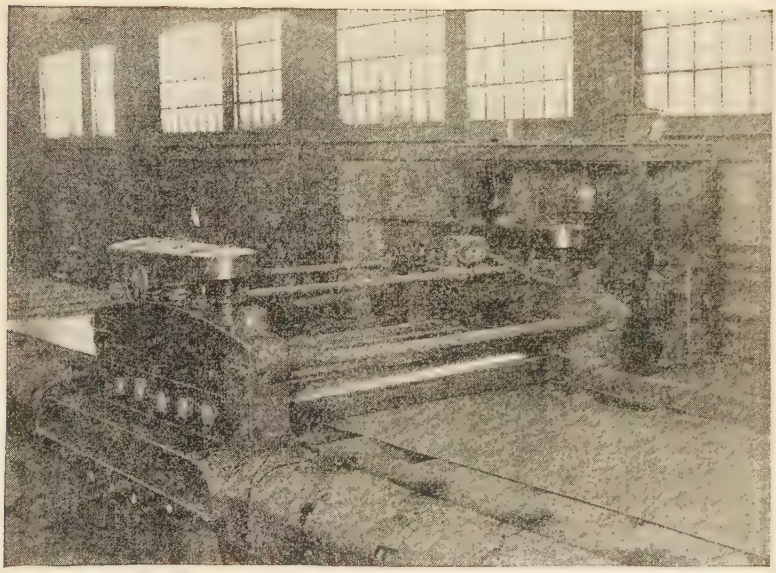


Fig. 146. View of Straightening Rolls in Operation.

line of separation between rollers. After the rolling is completed, the plate is passed by roll tables to a Hilles & Jones cold roll straightener. This straightener is constructed of two rows, one above the other, of small rolls, five in the top and four in the bottom row. The centers of the rolls in the top and bottom rows are alternated, so that the piece, on entering between the rolls, is given a long bend or sweep which is then removed by smaller sweeps until the piece, on passing out of the rolls, is quite or nearly straight. Two or more passes may be required to straighten some plates. The best work is done on plates about one-half inch thick, as they still retain enough heat when arriving at the cold rolls to be well and easily straightened. The rolls are operated by motors, and the draught is set on the mill by gears connected to a motor. From the rolling order sheets, the cold roller obtains the gauge of the plate when finished and then sets the cold rolls to take a plate of that gauge.

Laying-out and Stamping: After being straightened, the plates pass to the cooling bed and then to the marking tables. Here the heat number, slab number, customer's name, or mark, and plate dimensions are written on the plate by the marker. The plate is now ready to be laid out by the gauger. Laying out consists of drawing out in chalk the plate or plates as they are to be sheared, it being remembered that the plate as rolled from a slab may be made up so as to give material for two or more plates, in which case the plate as rolled is called a **combination.** As the plates

are still hot when gauged, allowance must be made for shrinkage, this allowance amounting to one-fourth inch in width and length for each hundred inches on plates up to one-fourth inch in thickness, and three-eighth inch for each hundred inches of length or width on gauges over one-fourth inch. This difference is necessary on account of the higher finishing temperature of the thicker plates. In case plates come to the marking table that will not make the plates ordered, on account of being too short or too narrow, the material must either be applied on another order or put in stock. Any plates with objectionable surface defects are rejected at the marking table and stocked. Plates stocked at the table are treated in the same manner as rejections, although they are not listed as such, because they have not been finished at the time of stocking. If a plate has a snake or is pitted on one end, this part may be sheared off and the remainder used on a different order than that for which it was intended. Plates that are too narrow to make the ordered plates are held until an order can be found calling for such a gauge, width and length as can be cut from them. It is a duty of the stock marker to replace such plates as are taken from the marking table. A report is made on the rolling order sheet, by the marker, of the number of plates made on an order, and the stock marker informs the office of all plates made from stocked material. While plates are being laid out they are stamped, giving heat number or slab number as is desired, and any other stamp that may be called for on the order by the purchaser. Heat number, slab number and size is also painted on the plates with white lead after they are marked. Some orders require that heat numbers, etc., are to be painted instead of being stamped, this being more generally the case on very light gauge plates. The method used in laying out a plate can be described from sketches, such as those shown in Fig. 147.

First, the width of the plate is taken at AB to determine the amount of stock over that of the ordered width plus allowance for shrinkage. The stock is then divided so as to give one-half to each side. Point C is set leaving the distance BC as excess stock. Point O is now set along XY in the same manner as point C. Line CO is drawn with a chalked string or a straight edge. Widths OM—EN—CP and others, if needed, are measured using line CO as a base. Line PM is then drawn by "the line drawer." A right angled square is now used to draw line CP at right angles to CO, thus squaring up the plate. The true length of the plate is taken along CO, using C as a starting point, and OM is likewise drawn at right angles to CO.

In case the plate is curved, the base lines must take the direction indicated in Sketch II in order to avoid scrap, and in case the length of the plate ordered is such as X′Y′ the plate cannot be made on account of the curve. This plate must be applied on orders that require lengths of approximately XI and QR, with widths and gauge such as can be obtained on the given plate. Whenever the number of plates ordered to the same

dimensions will justify the expense, patterns of wood are made for laying out. Sketch plates are always marked out to a templet, or pattern.

Test Pieces: In laying out the plate sufficient material must be given to allow for the test pieces that are required. On sheared plates both longitudinal and transverse test pieces are often taken.

Shearing: Three shears, one end and two side shears, are used on the one hundred forty-inch mill, and are so arranged that the plate does not require turning to shear the sides. The ends are sheared first, and the

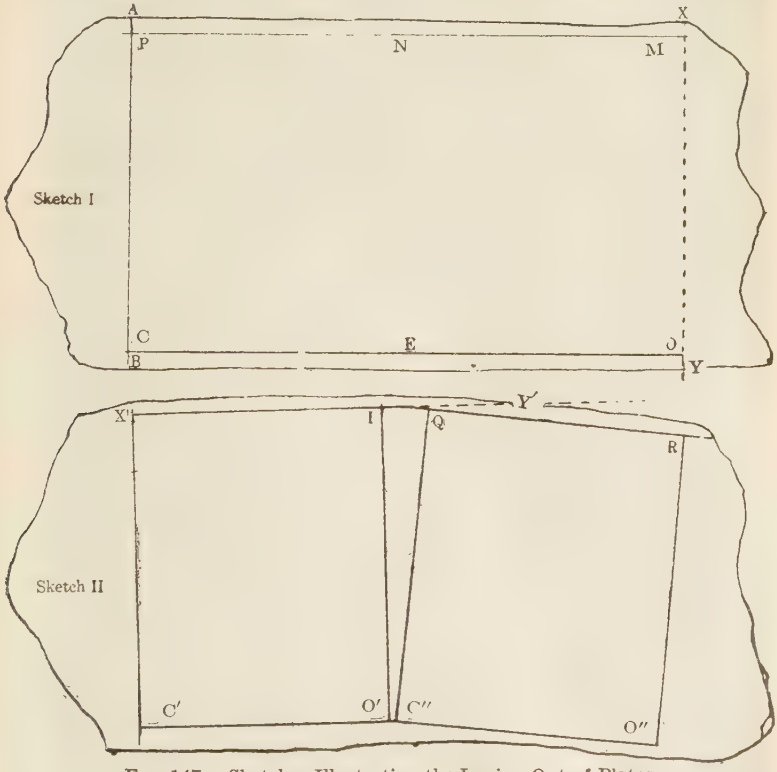


FIG. 147. Sketches Illustrating the Laying Out of Plates.

plate is then passed over castors to the side shears. This mill is also equipped with a rotary shear for heads and other circular plates, an alligator shear and a scrap shear.

Shearing Tolerances: It is evident, even to the casual observer, that conditions at the mills are such that shearing to exact dimensions is impossible. Observations made on any one mill will reveal many of these unfavorable conditions and also show that it is impossible to remedy them. The plates must be sheared in the order they are rolled, and, to keep up with the mill, rapid working is required, a condition that makes it difficult

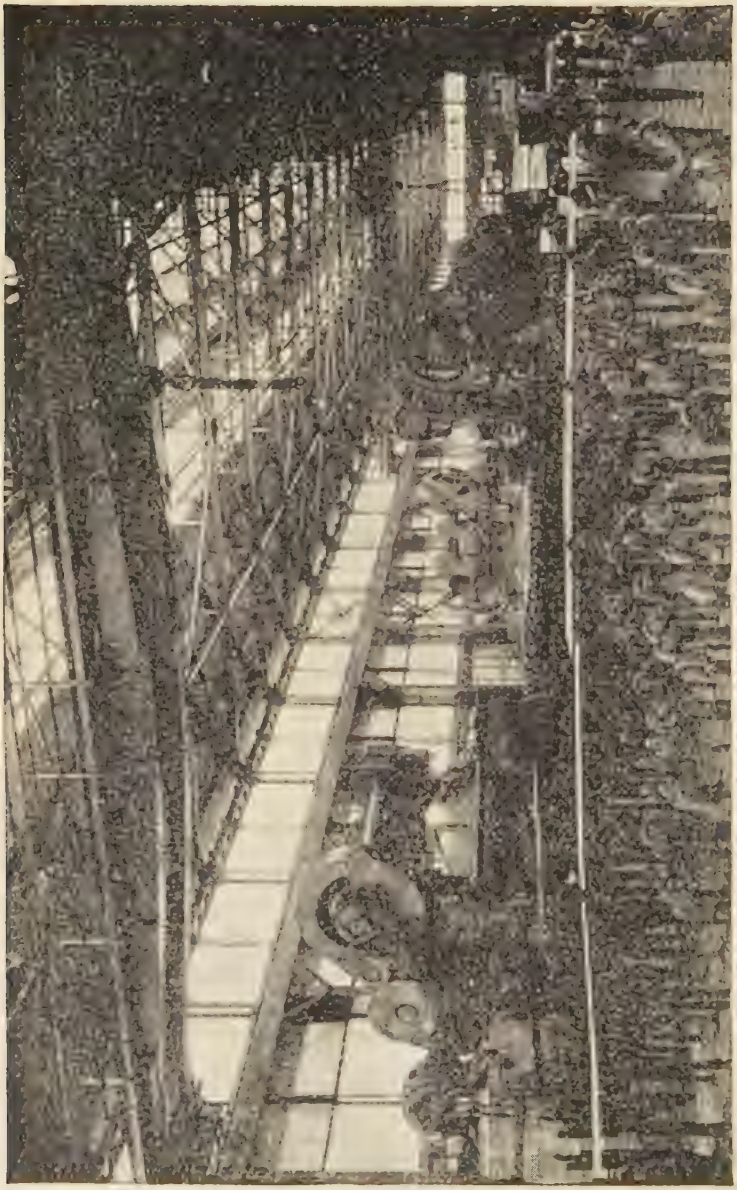


FIG. 145. View of Finishing Department of a Sheared Plate Mill, showing inverted casters to facilitate the handling of the plates and arrangement of end-cutting and the two side-cutting shears

to lay out or shear accurately. Owing to variations in the thickness of the plates and in the time required for rolling them, they leave the cooling beds at widely varying temperatures. Since there is no way of knowing accurately just what this temperature is at the time of laying out the plate, proper allowance cannot be made for the shrinkage, the total amount of which will also vary with the dimensions of the plate. Thus, while a plate ¼ inch thick and 100 inches long may require an allowance of ¼ inch for length, a plate one inch thick and 200 inches long may require an allowance of ⅞ inch. Finally, since no mechanical stops can be used on plate shears, the plates must be adjusted to position under the shear knife by eye-and-hand methods, which are not favorable to accurate work. Since the conditions in the different mills, such as length and type of cooling bed, kind of material rolled, etc., vary a great deal, it is practically impossible to fix standard variations covering all kinds of plates that will be just to the mills and the consumers alike. In justice to the former it should be stated that every attempt is made to shear as near to the exact dimensions ordered as the class of material would appear to call for and the mill conditions will permit.

Inspection for Size: After the shearing, all plates are inspected for size. If a plate does not measure up to the dimensions ordered or to within the tolerances permitted by the order department, it is rejected and returned to be applied on another order calling for the same grade of material.

Weighers: All plates are weighed separately, the weight and number of plates made being recorded on a copy of the rolling order sheet given to the weigher.

Checkers: The checker receives a copy of all rolling orders and checks each item for size and pieces ordered. On the weigher's copy of the rolling order, he lists the estimated weight of the plate as ordered so as to give the weigher the ordered weight, who, after taking the actual weight, can determine at once whether the plate will meet the specifications as to weight. The checker lists all plates ordered in the order book, and receives a copy of all orders to be rolled on the mill, so as to avoid the making of duplicates in case a plate is ordered twice. In case error is found in dimensions of plates listed on the rolling order, the checker informs the roller and marker. The checker also lists all plates made in the order book, thus keeping a record of the plates still on order.

Slip-maker: The slip-maker's duty is to make a form giving the following information: Mill, slip number, customer's name, Carnegie order number, sheet number of order, heat number, number pieces made, dimensions, marks and actual weight. The dimensions, etc., are to be taken from the plate, formerly painted on by the painter at the marking table. A copy of the rolling order is at the disposal of the slip-maker to aid in identifying plates, but data cannot be taken from the order without seeing the marks on the plate, in as much as certain plates may, at the marking tables, be applied on orders different from those they were originally intended for. A new or separate slip is made out for each order number. The signature of the slip-maker is required on each slip for identification.

Recorder: The duty of the recorder is to test the weights of all plates made and note the turn on which they were rolled and sheared. The record here taken is the final record of the product made and must be taken very accurately. Special forms are used for recording, showing turn, numbers, weight, descriptions of plates, etc. Special sheets are made for alloy steels and small pieces that are inspected at the time of measuring for size.

SECTION III.

UNIVERSAL MILL PLATES.

The Forty-eight-Inch Mill at Homestead as an Example of Universal Plate Mills: This mill consists of two horizontal rolls and four vertical rolls, two on each side of the horizontal ones, all contained in the same housings and driven by the same engine. This construction makes the mill a very complicated piece of machinery, a detailed description of which would be too lengthy to attempt here, so only such matters as are necessary to an understanding of the working of the mill will be discussed. While the working surface of the horizontal rolls is only four feet, which is the same as the maximum spread of the vertical rolls, the total length of the rolls is thirteen feet one inch, of which length twenty-four inches makes up the wobblers, forty-five inches the necks, and forty inches, twenty inches on each side, crosses the spaces in front of the vertical rolls, which must stand between the housings. These rolls are connected to the engine and are driven in the same way as the ordinary reversing mill. The total lift of the horizontal rolls is twenty inches. The screw down on these rolls is the same as that on the sheared plate mill, and the same form of graduated drum is used to indicate the lift of the rolls, or the gauge of the plate. The vertical rolls, whose centers are located three feet one inch from the centers of the horizontal rolls, are seventeen and one-half inches in diameter at the body, and the height of their rolling surface is two feet four and one-eighth inches. They are provided with bearing boxes at both their tops and bottoms. A five-inch collar on the upper end of the lower neck rides on a side bearing in the bottom box which furnishes the vertical support for the roll. A screw, bearing on a frame attached to the bearing boxes and actuated by an electric motor, furnishes the means by which the pressure for rolling is applied to these rolls; for spreading them hydraulic jacks are used. Large discs, graduated on their circumferences and mounted on the screws, indicate the spread of the vertical rolls. As already stated, these rolls are driven through a system of gears by the same engine that drives the horizontal rolls. Beginning with the engine, the power is transmitted to the horizontal rolls in the usual manner for reversing mills, while the drive for the vertical rolls is taken off the upper pinion. Upon the prolongation of the outside bearing of this pinion, a second gear is keyed. This gear meshes with two idlers, one on either side, which in turn mesh with gears mounted on the

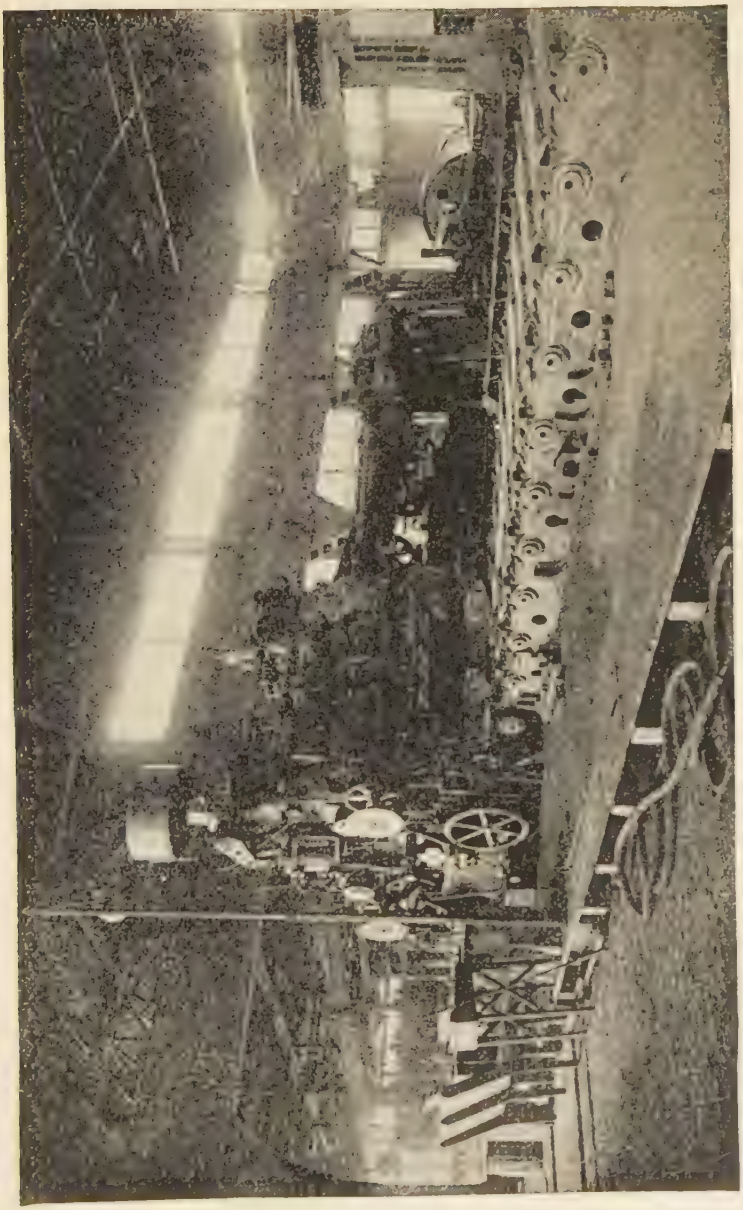


Fig. 149. View of the 48-inch Universal Plate Mill from the Delivery Side

ends of the two drive shafts for the vertical rolls. These shafts then extend to and across the roll housings, where they are supported by suitable bearings. On the section of these shafts included between the roll housings are mounted four sliding miter gears which mesh into similar crown gears keyed to the tops of the rolls. Through these gears the peripheral speed of the vertical rolls is adjusted to equal the speed of the horizontal rolls, and never more. Hence, the vertical rolls may be used on the piece only on the entering side of the passes, because if the vertical rolls were used on the delivery of the plate the greater speed of the piece due to the elongation produced by the horizontal rolls would jam the material between the two sets of rolls. The rolling of the piece on the entering side is preferable to rolling on the delivery side, as then thin plates would tend to buckle or bow up in the center on applying pressure from the vertical rolls. These rolls cannot be brought closer together than twenty inches. Hence, the mill has a range in width of plates from twenty to forty-six inches, as it is necessary to allow about 2 inches for the drafts required to keep the edges true.

The Operation of Rolling: Rolling universal mill plates involves most of the difficulties of rolling sheared plates, and in addition there are several features, due to the vertical rolls, that are not peculiar to sheared plate mills. Thus, the piece must always enter the mill at right angles to the horizontal rolls, as otherwise the action of the vertical rolls will cause the plate to buckle or curl or jam between the rolls. As the plates rolled on this mill are in very long lengths, the slightest variation in the spacing of the horizontal rolls shows up as a decided camber in the plate as it runs out on the table. To correct this defect, which is prone to occur on universal mills, a spanner block is placed under the screw down on the roller's side of the mill. By means of a spanner bar and a sledge hammer, this block may be turned and the proper adjustment made on this end of the upper horizontal roll to cause the plate to roll straight. As to the draught and manipulation of the horizontal rolls, the plate is reduced in the same way as on the sheared plate mill. On the vertical rolls the greatest draughts are taken in the first few passes, the object being to reduce the piece to the desired width as quickly as possible, after which the pressure on the vertical rolls is just sufficient to hold the piece to width. This mill rolls many plates directly from the ingot. Ingots intended for this purpose are rectangular in cross section, being from one to two inches wider at the smaller end than the width of the plate desired. In beginning the rolling of these slab ingots, the rollers prefer to have the small end enter the mill first, as in this way the suddenness of the pull on the mill is avoided and the draught can be more easily adjusted, but, for several reasons, many plates are rolled with the butt end of the ingot entering first. The chief objection to rolling plates directly from ingots is that the pipe and central line of segregation is rolled into the plate, and in order to avoid it the scrapping of a large amount of finished material is necessary.

Straightening, Marking and Shearing U. M. Plate: From the rolls, the plate is carried on live roller tables to the two cooling beds, which extend in opposite directions from both sides of the receiving table. Here any curve or camber is removed from the plates by clamping them tightly to a straight edge. The buckles thus produced on the edges of the plate are then flattened out with wooden mallets. While the mill is provided with a machine straightener, similar to the one employed at the one hundred forty-inch mill, it is seldom used, the general practice at universal plate mills being to straighten the plates in the manner described above. Every plate rolled on this mill has the name and letters "Carnegie, U. S. A." rolled into it at intervening spaces of seven feet. While on the cooling beds, the plates are marked off for length, the heat number is stamped on, and the slab number, size of plate, order number and the customer's name is marked on with white paint. The plates then move on to the receiving tables, which carry them to shears, where the plates are cut to length. A large shear used for splitting plates is also provided. Unless otherwise specified, two longitudinal tests for the physical laboratory are taken for each order or on each heat of steel; one test is taken from the top of the ingot, and the other from the bottom. The weighing, recording, and inspection of the plates are then conducted as for sheared plates.

Advantages of Universal Mill Plates: While the effect of the one way rolling on universal mill plates, as will be explained shortly, is such as to require care and discrimination in their use, they, nevertheless, possess certain advantages over sheared plates that make them more desirable for some purposes. First, the possibility of producing plates of great length with a rolled edge makes them available for many purposes, such as girder construction, for which sheared plates are not suitable. Second, the ability to roll to fairly exact widths reduces shearing costs to a minimum. Third, the rolled edge eliminates all costs to the purchaser for machining. As a fourth advantage the greater tonnages that these mills are capable of producing may be cited, because this tends to keep the first cost to the customer low.

Physical Properties of Plates: The effect of rolling on the physical properties of steel is now generally recognized by the users of plates, and specifications are usually written accordingly. In a previous discussion of this subject it was made plain that the controlling factors during rolling are the amount of work done and the temperature above the critical at which the rolling is completed. To these there should now be added the manner in which the rolling is performed. Attention has been called to the different methods of rolling plates in the preceding description. It will be recalled that the plate may be rolled from the slab with one reheating or from the ingot direct without reheating. As to the difference in effect produced by these two methods, there is little data on the subject, but reasoning from the theoretical standpoint, there should be no difference, except that produced in giving direction to the fibres. The directional effect upon the mechanical properties due to the fibrous structure has

already been explained. Rolling from the ingot will not permit the cross rolling necessary to overcome this defect. However, the abandonment of the method of rolling from the ingot is not to be advocated in all cases, for the directional effect of the fibrous structure is not of equal importance in all material. Again, in the rolling of the slab, it was pointed out that all the rolling may be in one direction only, or the plate, in the case of sheared plate, may be rolled both transversely and longitudinally. Here a noticeable difference is observed to result from the two methods of rolling. For example, if a slab be rolled in one direction only and a longitudinal and transverse test piece be cut from the resulting plate, little difference in tensile strength will be observed in pulling the two tests, but a marked difference in ductility will be found. Thus, the longitudinal piece will give from 4 per cent. to 7 per cent. greater elongation than the transverse piece, and 10 per cent. to 15 per cent. greater reduction in area. This difference is to be attributed to the fiber structure produced by the one-way rolling, for it is not noticeable in cross-rolled plates. Concerning the amount of work and finishing temperature, the ductility is affected in a somewhat erratic way, while the tensile strength is increased by increased work and lower finishing temperatures. Thus, a thin plate will show a very appreciable increase in tensile strength over a thick one rolled from the same slab or ingot, and to obtain the same strength in plates of different thicknesses it is necessary to employ chemical control. The following table is intended to show approximately the variations in the carbon content, other metalloids being constant, that should be made to produce plates of uniform strength when varying in thickness as indicated.

Table 65. Showing Variation of Carbon Content with the Thickness of Plates to Give the Same Strength When Finished at the Usual Temperatures.

Thickness of Plate	Carbon Required
3/16"	12%
7/16"	15%
1/2"	17%
3/4"	18%
1"	19%
1 1/2"	20%

Inspection of Plates for size and weight is made by mill inspectors, while inspection for surface and other defects are made either by mill or customer's inspectors. Certain surface defects, as snakes and surface marks, may do the plate no harm if they do not extend too deep into the metal, and may be ground out with any suitable device. For this purpose a movable electrical grinding wheel is employed. The rigidness of the inspection may be surmised from a glance at the inspector's list of causes for rejection, which is here appended. Most of these reasons are self-explanatory, while others have already been discussed, so that no further explanation is required.

Table 66. Defects for Which Plates are Rejected.

Defects Acquired or Caused From					
The Ingot	In Heating	In Rolling	In Laying Out	In Shearing	From Many Sources
Blister	Burnt	Split	Wrong Dimensions	Scant	Snake
Pipe	Bricked	Slivers	Made wrong	Bad Edge	Seams
Slivers	Scabby	Dished		Crop end	Test lost
Seams	Cinder spot	Pitted		Test piece cut	Duplicate
		Scored		Knifed	Broken
		Buckled			Ground too deep
		Over weight			Cracked
		Under weight			Tests are not within specification
		Over and under gauge			
		Scale			
		Cambered			
		Laminated			
		Roll marked			
		Bad edge (Universal Mill Plates only)			

CHAPTER VIII.

THE ROLLING OF LARGE SECTIONS.

SECTION I.

RAILROAD RAILS.

Development of Rail Manufacture: Dating from the invention of the steam locomotive, the railroad rail represents one of the first sections with which the rolling mill operators had to deal, as well as one of the most difficult and certainly the most important. The importance of the railroad as a factor in modern civilization and progress is recognized by all, and that the rail is a most vital part in railroad operations is just as evident. With the advancement in speed of travel and weight of loads carried, more and more has been required of the rail, until to-day no material is subjected to more severe punishment in service than the railroad rail. Exposed to the weather at all times, it is subjected, under constantly varying conditions, to immense compression and bending stresses, shocks, vibrations, friction and wear. The form of the rail, then, should be such as will give the greatest transverse strength, provide abundance of metal for wear, present a wide base for fastening to the cross tie, and still, for the sake of economy, be of the lightest section possible. Now, it so happens, that the form that best meets all these requirements is the section known as the American Tee Rail. It also happens that this section was, in the early days of rolling mills, one of the most difficult sections to roll, mainly on account of the wide flange. The history of rail development as indicated in the sketches of Fig. 150 gives evidence of this fact.

Thus, the first real departure made from the original strap rail of 1808 was the chair rail of 1820. As the chair of this rail was expensive, an attempt was made in the section of 1831 to roll a rail with a wide and relatively heavy flange on the bottom to replace this chair. The difficulty of rolling the flange led to the better balanced bull head of 1837, the U-shape of 1844 and the pear head rail of 1845. Then came the compound rail of 1856 and the form of 1860, which is the U-shape of 1844 with the lower parts closed in and welded to form the web. As neither of these forms proved serviceable, a demand for more metal in the head for wear forced a final return in 1865-8 to the tee shape with wide thin flange. From this date the design of rolls, quality of material, and lay-out of the mills has gradually been improved until at the present time the American rail mills are not only producing the largest tonnage of the world but also rails of the best possible grade.

Methods of Rolling Rails: Rails were originally rolled on the pull-over mill, and then on the reversing mill, which in England is the type of mill still employed for this purpose. But in this country all rails are rolled on the three-high mill, which formerly was usually made up of a single train of three stands driven with one engine. With the increase in the size of the section, which has almost doubled in weight within the last quarter century, and the growing demand for larger quantities and better quality in the product, a more advantageous lay-out of the mills for handling this

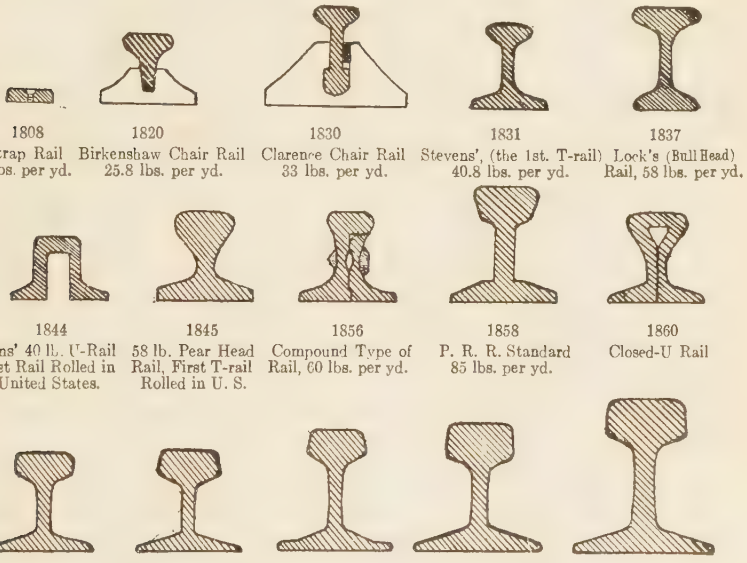
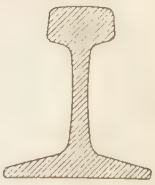


FIG. 150. Sketches of Rail Sections Illustrating the Evolution of the Railroad Rail in America.



material became necessary. The more modern rail mills will, therefore, consist of two or three trains, each separately driven and made up of one or more stands of rolls, all so arranged that the rolling of the piece in any one stand is complete before it is passed to the next succeeding one. With this arrangement the output of the mill is greatly increased without much increase in the speed of the rolls, because different pieces may be rolling at different stages at the same time, and the turning of the piece between passes is avoided. As to the heating of the steel, rails may, as previously

stated, be rolled either from blooms that have been reheated after having been rolled from the ingot, or on the original heat of the ingot. The latter method, which was introduced a few years ago mainly to save the extra cost of reheating, was until very recently looked upon with favor both by the manufacturer and the consumer, who believed that the scheme would have a beneficial effect upon the quality of rail produced, due to the fact that the material was necessarily finished at a low temperature. Within the last decade, however, sentiment appears to have taken a swing in favor of reheating, because, as is claimed by the advocates of reheating, the increased speed of rolling combined with the heavy draughts required to complete the rolling on the original heat is liable to produce a condition favorable to the formation of fractures. The effects of too rapid reduction have already been discussed. For the same reason the temperature of the ingot is kept high, which fact increases the danger of overheating. In addition, the difficulty of keeping the finishing temperature constant, presents a serious problem. On the other hand, by reheating the bloom the two initial rolling temperatures may be lower and be kept more uniform, and the shaping of the rail may progress more leisurely. As to the manner of forming the section, there are two methods of rolling, known as the flat, or slab-and-edging, and the diagonal, or angular, method. To impart even a slight understanding of these methods requires a lengthy explanation; but in the proper design of the various passes for the progressive forming of the rail, as for any section, lies the crux of the rolling process. Therefore, as the subject is one of great interest, an attempt is to be made to discuss the matter in as brief and comprehensive a manner as possible under the headings that follow.

How to Study Roll Design: The best way to explain roll design is by an example, for it is as yet an art acquired mainly by experience. While subject to natural laws, the scientific aspects of the subject have not been fully developed, and the roll designer has few rules to learn. This condition tends toward individuality in designing, with the result that it is seldom two designers will be found to do the same thing in the same way. To serve as such an example the flat method of rolling as carried out at the Edgar Thomson Works will be described, because, of the two methods of rolling, this is the older and the one more generally employed. Before beginning with the example, however, some preliminary explanations are required.

Precautions to be Observed in Designing the Rolls: Of course, the first consideration in roll designing is to produce a finished piece of the correct size and form, and this must be done by spreading, bending and directing the flow of the steel. The ease with which this forming is done depends on the plasticity of the metal, which in turn is affected by the kind of steel, whether open-hearth or Bessemer; the grade, whether high or low carbon; and the temperature. With the speed of the rolls fixed, the temperature confined to a very narrow range, and the kind and grade of steel

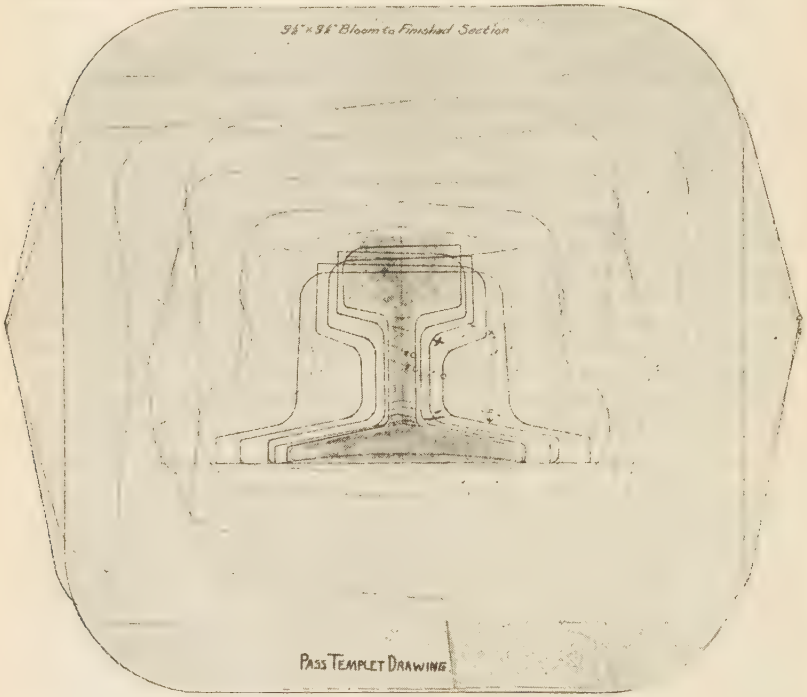
given, the only instrumentality remaining in the hands of the roll designer is the size and shape of the passes, and in part of these, at least, the size will be governed by the size of the bloom. In designing the passes, a good designer will endeavor to work the steel in such a manner that the quality of the product will be benefited, and no defects will be developed. The defects that require constant care are fins, laps, overfills and underfills. Laps may result from fins or a collaring of the piece in the rolls; overfills, from worn rolls, bad or improper design; and underfills either from bad design or incorrect adjustment of the rolls.

Stages of Reduction: The formation of the rail from the bloom may be looked upon as taking place in three steps or stages. The first stage, called the roughing, is merely one of preparation; in it a large amount of work is done, but this work is expended mainly in reducing the size of the section and elongating the piece. At the Edgar Thomson Works the piece is reduced in seven to nine roughing passes. In the first four to six passes, rolling by the slab-and-edging method, the section retains the rectangular shape, while in the next three passes a little shaping of the flange is begun to prepare the piece for the first finishers, in which there are five passes. These passes are given names in order, indicative of the nature of the work they are intended to perform, as follows: Slabber, first former, second former, third former, and the leader. The leader is the pass just previous to the finishing pass, which is located in a separately driven stand of two-high rolls. With this explanation of terms used, the different steps in the design of the rolls and the rolling may now be traced. They are as follows:

The Section: No original designing of section is done by the roll designer. The first requirement in the rolling of a new section is, then, that the roll turner be supplied with a drawing or print of the section, which must be accompanied with all the dimensions, preferably indicated on the print. The weight of rail desired or expected should also be given. Here the matter of dimensions is of extreme importance, for the designing of the templets cannot be started until each and every dimension required is given. These dimensions not only include linear measurements, such as height of rail, width and thickness of parts, but radii of all curves, and amount of slope on inclined surfaces expressed in degrees or percentages.

The Cold Templet: With all the necessary information before him, the first step taken by the roll designer is to prepare a drawing for the cold templet. This templet is made of brass and represents an exact section of the rail when cold. This drawing is constructed on the axis of symmetry of the rail, which is the vertical line drawn through the center of the head, of the web, and of the flange. On this line the section of rail is symmetrically constructed to the dimensions given on the drawing, all the dimensions being made with extreme care and accuracy. All measurements are made with micrometers or steel rules. If a rule is used a magnifying glass is employed to take the readings. The construction lines are made as fine as possible. Even the contraction and expansion of the drawing paper, due to

the varying humidity of the atmosphere, is taken into consideration, and the proper allowances are made. With this very accurate drawing completed, the area of the section is measured with a planimeter in order to check up the weight of the section. If this weight should differ from that given on the original print or drawing, the templet drawing is checked and, if correct, the customer is notified that the actual weight will not be as specified. No further work may then be done till this question of weight is settled, when the brass templet will be made from the drawing.



PASS	HEAD	WEB	BASE	TOTAL	% RED	SPREAD
FINISHING	14 4	5 4	12 1	31 9	5 %	1/8"
LEADER	15 2	5 7	12 7	33 6	15 %	3/32"
3RD FORM.	17 9	6 7	14 9	39 5	2[illegible] %	3/32"
2ND FORM.	22 4	8 4	18 6	49 4	24 %	3/32"
1ST FORM.	29 5	11 1	24 3	64 9	22 %	3/32"
SLABBER	37 8	14 2	31 2	83 2		

FIG. 151. Pass Template Drawing—Slab-and-Edging Method of Rolling Rails.

% Reduction in Passes.

	No.	Pass	% Red.
2nd. Rough	A	Finishing Pass	5. %
	B	Leader	15. %
	C	3rd. Forming	20. %
	D	2nd. Forming	24. %
	E	1st. Forming	22. %
	F	Slabber	23. %
1st. Rough	G	9th. Pass	24.5 %
	H	8th. "	24.5 %
	I	7th. "	22. %
	J	6th. "	27. %
	K	5th. "	22.8 %
	L	4th. "	17.7 %
	M	3rd. "	28.8 %
	N	2nd. "	17. %
	O	1st. "	14.5 %
	P	Bloom	

The Hot Templet: The next step, which is really the first step in designing the roll passes, is the making of the hot templet. This templet is exactly like the cold templet, but larger in size to allow for contraction, as it represents the section of the rail at the finishing temperature of rolling. The co-efficient of contraction, or exact amount to allow here, is determined by experience. From this hot templet the various passes are designed successively as the experience and judgment of the designer dictates.

The Pass Templets: In designing these templets, the designer constructs each in a drawing showing the different passes superimposed upon each other as in the accompanying illustration. In actual practice these drawings are constructed full size, but for convenience in printing this photograph is three-eighths natural size. This illustration represents the passes for a light rail rolled by the slab-and-edging method. In this method, the axis of symmetry of the rail coincides with the pitch line and is parallel to the train line of the rolls, as can be seen from the print. The more darkly shaded area in the photograph represents the hot templet, with the pitch line or axis of symmetry drawn through it, and from it the grooves in the finishing pass are cut. From this pass the roll designer works back to the bloom. As a preliminary step toward designing these passes, a table like that shown attached to the photograph is prepared. In a vertical column, headed **pass,** are placed the names of the various passes from slabber to finishing, while the figures in the columns designated as **head, web,** and **base** represent the sectional area of the different passes for these parts expressed in pounds per yard, which is directly proportional to the area in square inches. This table is prepared as follows: The areas of the different parts of the rail are fixed by the hot templet. In this section the metal was proportioned in the design so as to give 14.4 pounds per yard in the head, 5.4 pounds per yard in the web and 12.1 pounds per yard in the flange, the total being 31.9 pounds per yard, which is heavier than the cold section by 1.4 pounds per yard. This difference is due to the fact that the weight of the hot section is calculated as if it were cold, a correction for difference in gravity not being necessary for this purpose. Next will be put down under the column headed **per cent. reduction,** the amount of reduction expressed in per cent., which from experience and judgment, the designer thinks will be best. In this case these amounts are as follows: In the finishing pass one-thirty-second of an inch reduction on each side of the web is allowed for the marking; in the leader, 15 per cent.; in the third former, 20 per cent.; in the second former, 24 per cent.; in the first former, 22 per cent; and in the slabber, 23 per cent. From these figures the areas of the different parts of each pass are calculated, and the blanks in the table filled in as shown. Next, the amount to allow for spread of the piece from one pass to the other is decided upon and placed in the column headed **spread.** This allowance is expressed in fractions of an inch and is measured and allowed for along the axis of symmetry as shown by the positions of the rail heads in the photograph. With the reduction for the various passes

and their parts thus apportioned, the designer then proceeds to draw in the passes, as designated in the photograph by the letters a to p, and in doing so he keeps the following points constantly in mind. First, is the

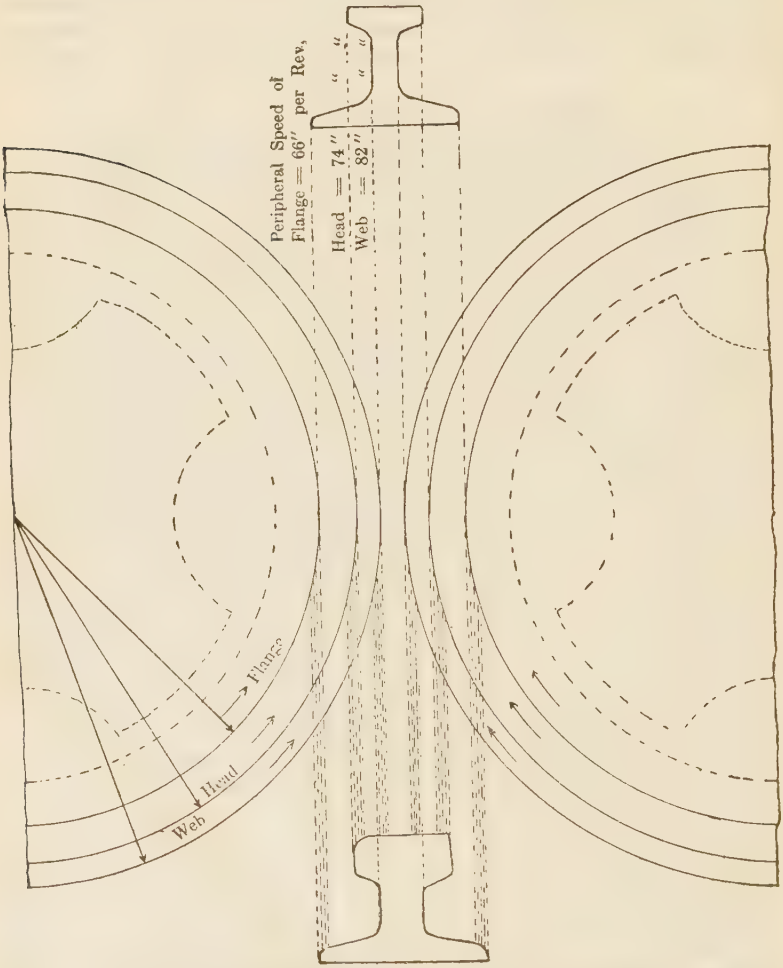


FIG. 152. Showing Difference in Peripheral Speed of the Rolls at Web, Head and Flange.

danger of forming fins. As an aid in avoiding these defects, the piece is passed through the mill so that each side of the pass alternately enters an open and closed side of the groove. How this is done on the three-high

mill without turning the piece can be seen from a study of Figs. 153-154-155. Even with this arrangement fins would still be formed if the passes were not properly designed. To avoid all danger of fins two tricks of design are here resorted to. Thus, in the leader, or pass *a*, the corner of the head, which is to come opposite the openings between the rolls in the finishing pass, is well rounded off, so that the spread or flow of the metal will be taken up in filling out this rounded corner and none will remain to be forced into the clearance. For the same reason, that half of the flange on the same side of the rail is left much shorter. It will be observed that this provision is made in all the passes down to the slabber. From the photograph it will be noticed that most of the work from the slabber is done along the fishing of the rail, the metal being forced horizontally from the central portion of the slab toward the head and flange and vertically into the web. This is done by holding the working surface under the head and on top of the flange at the angles shown. In designing this part of these passes care must be taken to see that the line XY at the bottom of pass *d*, for example, is not greater than X′Y′ at the top of its preceding pass *c*, as otherwise the piece would be collared when it entered *d*. Great care is necessary in distributing the reduction of each part to prevent the metal flowing away from parts where it is needed. Thus, for example, if a too great reduction in the web takes place in one pass, it will produce a flow of metal away from the head, causing the latter to be underfilled. The cause for much of the trouble of this kind lies in the different diameters of the pass, which causes a different roll speed for head, web and flange, and hence different rates of elongation. If the elongation at one point, due to increased speed of the rolls, is not balanced by elongation produced through compression at the point of less speed, the section will be imperfectly formed, or cracks will result. The accompanying illustration (Fig. 152) will help in understanding this point. In all reduction, it is a good plan to keep the angle of bite well below the limiting angle of 30°. In the first roughers the difficulties of design are approximately the same as those of the three-high bloomer, and no further explanation of these passes is required.

Preparation for the Rolling: After the passes have all been constructed properly in the drawing, a set of working templets, including both male and female for the cold templet, is made from the drawings. The working templets may be of steel. These templets may number from the slabber down only, as the roll designer strives to keep the roughing passes of such shapes and sizes that the same set may be used for a large number of different sections of the same general design. When completed they go to the tool shop, where they are used as patterns in making a set of tools for turning the rolls for the section. For the last six passes, that is, numbering from the slabber to the finishing, inclusive, twenty-two different tools are required for each type and size of rail. After shaping these tools to a little over size, they are tempered and then redressed to exact size before they can be used to turn the rolls. When ready, templets and tools pass to the roll shop, where the work of turning the rolls is done. Here the templets

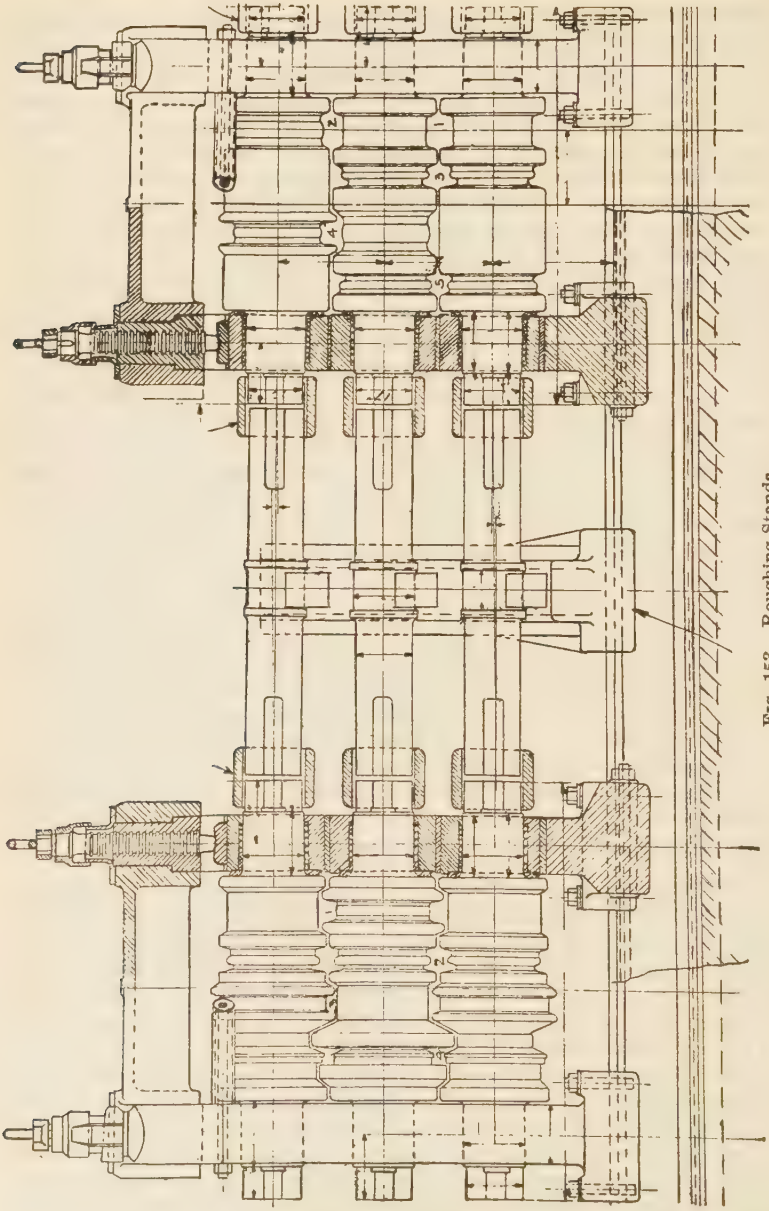


FIG. 153. Roughing Stands.

FIGS. 153–155. Arrangement of Rolls and Passes for

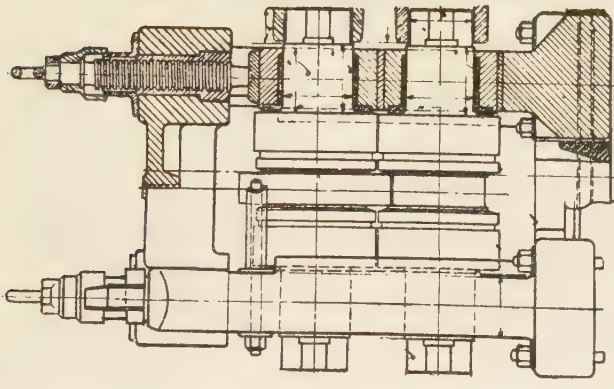


Fig. 155. Second Finishing Stand.

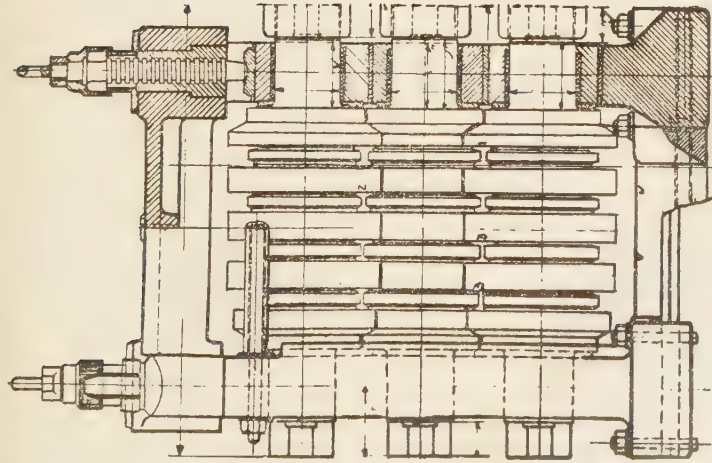


Fig. 154. First Finishing Stand.

Rolling Heavy Rails by the Slab-and-Edging Method.

are used by the roll turner in cutting the grooves, which must be of the exact size and shape of the templets. At Edgar Thomson the roughing rolls are adamite or sand rolls, more often the latter; the second rougher, or former, are sand rolls; and the finishing are chilled rolls.

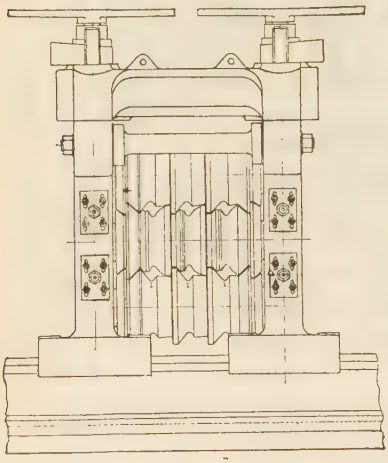


Fig. 156. 1st Roughing Stand.

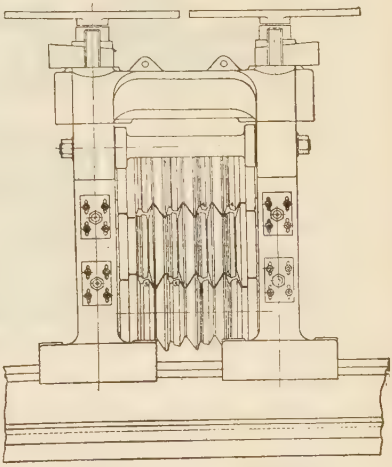


Fig. 157. 1st Finishing Stand.

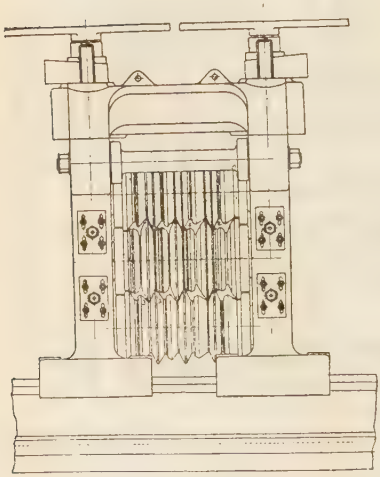


Fig. 158. 2nd Roughing Stand.

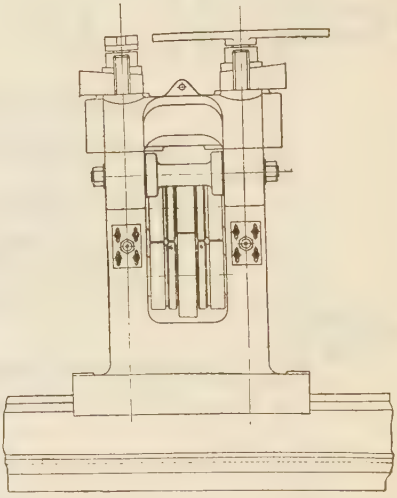


Fig. 159. 2nd Finishing Stand.

Figs. 156–159. Showing Arrangement of Rolls for Diagonal Rolling of Rails from Billets.

The Diagonal Method of rolling is represented on the accompanying cut of a light rail mill where this method is employed altogether. It differs from the slabbing method in that the shaping of the rail is begun with the first pass in the roughers and, instead of first compressing the bloom to a smaller size and then forming the section partly through compression and partly by spreading, the process is one of compression from beginning to end, as must be evident from observing the position of the piece in passing through the rolls. From a quality standpoint the method is thought to possess some advantage over the slabbing method by virtue of the fact that a greater amount of work is done on the tops of the head and flange, where it is needed. From the operator's standpoint it would seem to have both advantages and disadvantages. As an instance of the former, it is pointed out that the angular grooves make it easier to redress the rolls and tend to give them a greater life, because the cuts to restore the section need not be so deep. To restore a section of the flat grooving, cuts as deep as one-half inch are usually required on smaller sections, while as much as three-fourths inch is needed on the larger ones. The chief disadvantage of using the method lies in the great side thrust of the rolls, which is very undesirable and difficult to provide for. It also requires more roll space than the flat method for the same number of passes.

The Mills: There are four rail mills at the Edgar Thomson plant, but one of these, the oldest, is used exclusively for rolling sheet bar, billets, etc. Of the mills used for rolling rails, No. 1 mill is the older. It consists of three stands in tandem, each separately driven. The first roughing stand is driven by a 40″ x 78″ x 60″ horizontal vertical compound condensing engine, and the rolls are twenty-eight inches in diameter. The second stand, driven by a 50″ x 78″ x 60″ tandem compound condensing engine, contains rolls twenty-seven and one-half inches in diameter. The finishing stand, which is two-high, is made up of rolls twenty-five and one-half inches in diameter, and is driven by a 32″ x 56″ x 48″ tandem compound condensing engine. This mill, originally built for a twenty-four-inch mill, is evidence of the rapid increase in the size of roll sections and the extremities the mills are put to in order to meet the demands made upon them for heavier rails. The mill now rolls rails from twenty-five pounds to one hundred pounds per yard. The No. 2 mill was completed in the early part of 1916 and is designed to roll rails up to one hundred fifty pounds per yard, which weight, it was hoped, would meet all demands for some years to come. Up to 1924 the largest section rolled was a hundred thirty-pound rail, but the hundred fifty-pound rail is now being considered. In this mill all the rolls are thirty-two inches in diameter, when new. The pitch of the pinions is twenty-nine inches, which adapts the mill to rolls as small as twenty-eight inches in diameter. Like the No. 1 mill, the No. 2 is made up of three trains in tandem, but the first roughing train contains two stands, in order to provide ample roll space for rolling large sections by either the flat or diagonal methods. The bodies of the rolls

in the first three stands are sixty-four inches in length, while in the finishing this dimension is reduced to forty inches. The first and second trains are driven by 50″ x 78″ x 60″ tandem compound engines. The fly wheels on these engines weigh 100 tons each, and the speed of the engine is about 60 r. p. m. The third train is driven by a 44″ x 74″ x 54″ horizontal vertical compound engine, which has a speed of 65 r. p. m. The first or roughing stands on each of these two mills are served by lifting tables, and the intermediate stands by tilting tables. The No. 3, an eighteen-inch mill, employs 19″ x 42″, 19″ x 38″ and 19″ x 20″ rolls, and rolls rails from twelve pounds to forty pounds per yard. It consists of two trains in tandem, each of two stands; number one and number three stands, both three-high, make up the first train, while number two, a three-high stand, and the two-high finishing stand are in the second train. Each train is independently driven by a 1500 h. p. electric motor. Rails rolled on these mills have distinguishing marks. Thus, heavy rails rolled on the No. 2 mill have the sign, ⊖ , rolled on the web, and light rails rolled on the No. 1 mill are distinguished by the sign, =, similarly located.

Rolling Heavy Rails: After the rolls have been properly turned they are placed in the housing in their proper positions and carefully lined up. A trial rolling on a short bloom will then be made, and during this rolling the boss roller will watch the piece closely to see that it goes through the mill all right. If the section is a new one, the roll turner and designer will also be present to watch the trials. If the trial piece goes through the mill without causing trouble, a section is sawed, cooled, and examined by the roller and roll designer. In doing this, the piece thus rolled is gauged by means of the male and female templet which the designer has furnished the roller. If this section is found to be correct, the mill is then ready to begin the rolling, which is really the simplest part of the process. The roller watches the mill closely to see that everything is running right, and at frequent intervals will gauge and examine samples of the rails. In addition, he walks down to the cooling bed about every fifteen minutes to examine the rails for any defects that may be caused in the rolling, such as collar marks, underfills, roll marks, overfills, guide marks, cracks or seams. If he finds a defect in rolling, he hastens to make the necessary adjustments to correct the trouble.

Unavoidable Variations: One of the things that cannot be avoided in the rolling is the wear of the rolls. While it occurs over the entire surface of the groove the parts of the groove subject to fastest wear are those which do the greatest work. Referring to the photograph of the drawing for the pass templets, it may be seen where the greatest wear will take place. This results in a decrease in the fishing of the rail, as shown in the following sketch. It is also a difficult matter to keep the base perfectly flat, because the high collar in the finishing passes supporting this part of the rail tends to wear away the edges faster than at the bottom of the groove.

The slight overfill that results produces the defect known as the **rocking base.** This wearing is very rapid, and with the mill running steadily, one dressing of the rolls lasts but from twenty-four to thirty-six hours.

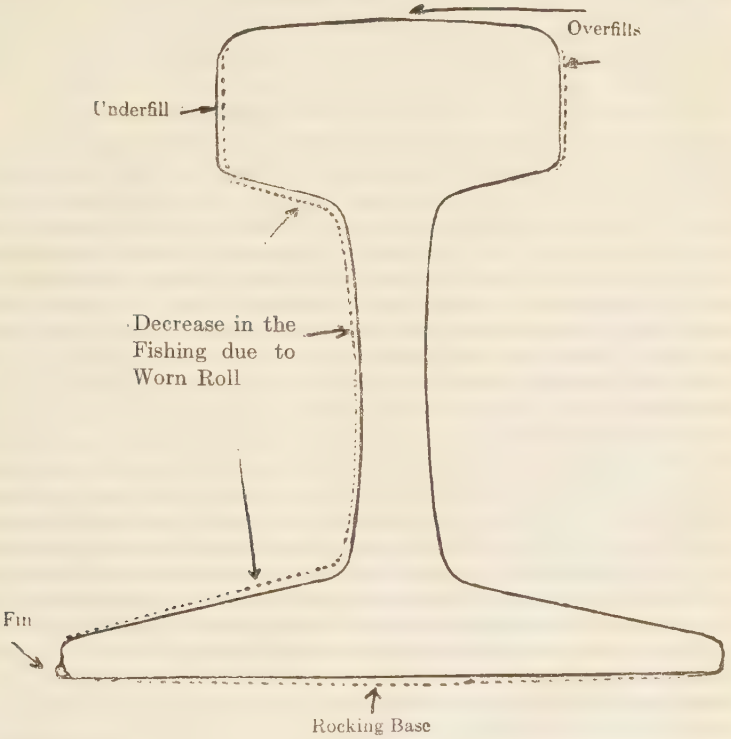


FIG. 160. Showing Defects in Rails Due to Wearing of the Rolls.

The Various Steps in Shaping of Rails: To trace the material from the ingot, the work begins at the forty-eight-inch mill previously mentioned, where the very slow speed and relatively great reduction gives more of the pressing and less of the stretching effect of rolling, and is intended to avoid much of the danger of tearing or cracking the ingot. The large fillets used in the grooves keep the corners of the ingot well rounded. This mill, reducing the ingot from 23½″ x 23½″ to 15½″ x 18½″ leaves less work than usual to be done on the three-high blooming mill which produces a 9½″ x 9½″ bloom. From the blooming mill the long bloom passes to the shears where the proper discard, which is varied in different specifications, is made, and blooms of different lengths are cut to suit the conditions. Large rails are

rolled two lengths to the bloom, while lighter ones may run into three lengths to the bloom. Leaving the shears, the blooms travel on roll tables to a distributing point, where they are sent to No. 1 and No. 2 rail mill furnaces or to No. 4 billet and sheet bar mill. The furnaces serving the two large rail mills, which extend parallel to each other and are housed in the same building, are arranged in one row at right angles to the mills and in such a manner that the blooms may be charged on one side and drawn on the other which is nearer the mills. From the rolls the piece passes on to the saws, and then to the finishing and inspecting department.

Cutting: For cutting rails, four high speed (1500 r. p. m.) toothed circular saws are provided. The saws are mounted over the delivery table on the free ends of tilting arms, whose axes are concentric with the drive shafts. Belts then connect the saws with their driving shafts, which are electrically propelled. On No. 1 mill all the saws are mounted on one shaft which is driven by one motor, but in No. 2 mill each saw is mounted on a separate carriage and is driven by an individual motor. The tilting arms are electrically controlled so that all the saws may be made to cut simultaneously. These saws are adjustable to cut different lengths from thirty to sixty feet, though thirty-three and thirty-nine feet are standard lengths. In cutting the rails, proper allowance must be made for shrinkage, which is nearly three-sixteenths inch per foot, or about seven inches for a thirty-three-foot, hundred-pound rail. The exact amount of the shrinkage depends upon the temperature at which the rail is sawed, hence many railroads specify the amount of shrinkage per rail, and in so doing fix the finishing temperature of rolling. The allowance should be not less than one-fourth inch over or under the length specified. Since the rails do not always leave the finishing rolls perfectly straight, it is not always possible to make a square cut, and one-thirty-second inch off-square should be allowed. Rails eighty-five pounds or over are rolled in double lengths, and on blooms on which tests are taken, six to eight feet is allowed for physical test pieces, which are cut from the ends of the piece. Smaller rails are rolled in triple lengths. Great care is required in adjusting the height of the saw blocks in order to avoid kinking or scratching the rail, and to secure a square cut. From the saws, the rails pass under a stamping machine, which marks the heat number and the position of the rail in the ingot, the latter being designated by letters beginning with A at the top of the ingot. At Edgar Thomson the A cut is discarded on all heavy rails. About sixty feet from the stamper is located the cambering machine which consists of a set of horizontal rolls with a vertical roll on each side, all in one housing, and set to bend the rail slightly so as to make the top surface of the rail convex from end to end. A scale located near the end of the delivery table is used for checking the weight of the rails as often as desired, before they are sent to the cooling beds. The No. 1 and No. 2 mills, being arranged parallel to each other, deliver their product to what may be considered a single large cooling bed, where the rails from both mills are slowly moved in one direction, which is toward the finishing room.

Recording: A complete record is kept of all the steel rolled in the mills from the time it is made in the open hearth or Bessemer converter until it is shipped. This work is done by the recorder, who traces the material through the mills, and is so complete that it is easy to show, not only the kind of steel from which each rail is rolled, but the heat, the number of ingot, and its position in the ingot. At these mills the work of tracing the material is much facilitated by the use of an electric signalling system.

Finishing and Inspection: The finishing room is arranged to the best advantage possible for handling the rails. In it are located the straightening and drilling machines (fourteen in number) in two rows parallel to each other and to the two mills, and extending in the same direction beginning at the mill side of the cooling beds. Between the row of straighteners and the cooling beds is a system of roll tables, which carry the rails from the beds and distribute them to the different straighteners. Here the rails are marked with a stamp to indicate the individual workmen responsible for this part of the work. The straightening machines, or gag presses, are provided with a bottom bed, on which the rail is supported at two points from below, and a top block which moves up and down between these two supporting lines with a fixed stroke of such length that the block will not touch the rail by about two inches at its lowest point. The block has a double face, each side of which is inclined toward the center line, where the faces cut each other. This form, combined with the different dimensions of the gag, a rectangular shaped block of steel which is inserted between the face of the block and the rail to be straightened, makes it possible to control the amount of bend that the rail receives and to adapt the machine to the different dimensions of a rail. For the different sizes of rails, the faces of the blocks are made adjustable by means of set-screws and liners, while for different sections different gags must be used. To straighten a rail, one workman is stationed in front of the machine and another at the end. By sighting along the rail, the man at the end locates the crooks in the rail and brings them under the blocks, while the man before the machine, acting under directions from the workman at the end, inserts the gag in such a way that the stroke of the machine will bend the rail enough to straighten it, which requires that the rail be bent beyond its elastic limit in order to give a permanent set. Next, the burrs made by the saws on the ends of the rails are cut off with chisels, and smoothed with a file. The rails are then given a preliminary inspection by an employee of the Company, in order to avoid unnecessary work being done on rails that may be rejected. As the inspection is completed, the rails are moved to the drilling machines, which are arranged in pairs and so spaced that, when one machine has completed the drilling on one end of the rail, it is moved under the other machine which drills the holes in the opposite end. These machines are each provided with three drilling spindles, the middle of which is fixed, and may be made to drill from one to three holes at one time. The rails are then moved sidewise through openings in the building to the inspection

beds where they are walked, or inspected, both by a company's inspector and by the customer's, if so specified. The outside inspection covers mainly surface defects, such as seams, slivers, guide marks, and pits that may have been overlooked by the inside inspector, and the bolt holes. The rails, having been measured and gauged by the inside inspectors and rollers, the dimensions are checked only at intervals by the outside inspector. The location of the defects are marked with chalk. If these are located near the end, that portion of the rail may be sawed off and the rail still applied on the order as a short of first grade. Rails that fall below the allowance as to length are also disposed of in the same way. If the defects are many or near the center, the rail is either classed as a number two or discarded and sent back to the mills. In both the inside and outside inspection, the rails are walked twice, once with the base up, again with the heads up. As the rails are accepted by the inspectors, they are counted, the number being checked up with the original order. Then they are picked up by immense magnets attached to over head electric cranes and placed in the cars where, after weighing, they are ready for shipment.

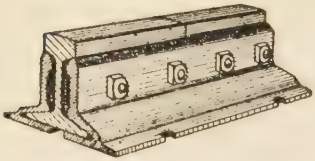
Light Rails: The rolling, finishing and inspection of light rails, as well as the material used, are somewhat different from the same operations for heavy rails. To begin with, the number three mill, in which most of these rails are rolled, is operated as a separate unit, practically independent of the rest of the works, and some of its product, which includes many items besides rails, is rolled from billets which are obtained from other works. For this reason check analyses and physical tests are rarely made on light rails, because the steel, on account of the relatively small tonnage of most of the orders, cannot be handled as separate heats. Consequently, even if such tests were made, there would be no way of identifying a rail as having been made from the same heat from which the tests were taken nor of knowing that the tests represented all the material in an order. In the case of rails, the billets are heated in one of two continuous gas fired furnaces and are rolled by the angular method on six or eight passes in the mill. Leaving the rolls, the rails are sawed into lengths of thirty feet or under and are passed to the cooling beds. When sufficiently cold they receive a preliminary inspection, in which they are measured for length, and then passed through a roll straightener to punching machines where both bolt holes and bond holes are punched. Since the roll straighteners straighten the rail in one direction only and usually fail to produce a perfectly straight rail, even in one direction, gag presses are employed to complete the straightening. As for heavy rails, light rails are subject to a second, though less rigid, inspection after all work is completed. The mill is also equipped with cold saws, but cold sawing is undesirable, for it works a great hardship upon the mill, increasing the cost greatly, due to extra labor and scrap loss. For handling the rails a large gantry crane of an improved form which travels on tracks laid on the ground is provided. Light rails are weighed in cars before shipment.

SECTION II.

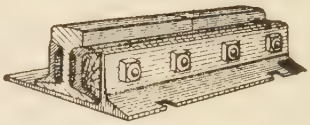
THE SHAPING OF RAIL JOINTS.

Rolling Rail Joints: As may be seen from the drawings on succeeding pages, rail joints have been made in so many different forms, it is impossible to select any one that would serve as an example to illustrate the problems involved in the rolling of the others. The accompanying prints (Figs. 163-164-165), show the shapes of the different passes for each of the three leading types of rail joints, namely, the common angle bar, the heavy or reinforced angle bar, and the continuous joint of the bed plate type. The insulated joints, with the exception of the continuous joint, are made up of plates comparatively simple to roll. In a general way, the non-insulated rail joints are more or less difficult to roll, being subject to all the drawbacks of the rail section and to many others in addition, due to their irregular section and lack of symmetry. In the common angle bar, for example, the angles at which the section is rolled are limited by danger of undercuts, and the shape of the passes in which the piece is necessarily reduced are favorable to the formation of laps and seams. If the joint has a depending flange, these dangers are multiplied, while the outstanding parts of a joint such as the continuous section of Fig. 165, by striking the rolls first or being a trifle colder than the rest, often prevent the piece from entering the pass rightly. For similar reasons, it is difficult to make guides that will properly handle this material, and it is prone to become cobbled or caught in the rolls of the tables. The base plate part of the continuous joint must be rolled at the angle as shown on the drawing, and this part later bent up hot at the splice bar shop to fit neatly the flange of the rail. The use of this joint is declining rapidly. After being rolled, usually in pieces about ninety-three feet long, the bars are hot sawed into three equal lengths, and sent to the splice bar shop, which is located at the Edgar Thomson Works. Here they are sheared to lengths required, punched, slotted and straightened by methods shortly to be described.

Methods of Finishing Rail Joints: While the finishing of rail joints bears no relation to the rolling of them and is a separate industry, yet for the convenience of the reader it is best to complete the subject now, rather than to postpone it for some other part of the book. In general, rail joints may be finished in one of three ways: First, all the operations of shearing to length, straightening, punching and notching may be performed upon the cold pieces without heating in any way, when they are spoken of as cold worked joints. Second, the bars may be heated, after shearing to length, and the work of punching, etc., be done while they are hot, after which they are allowed to cool in air. In this case they are called hot worked bars. Third, instead of cooling the bars in the air after hot working they may be cooled by immersing them in oil, when they are designated as hot worked and oil quenched bars. It will be observed that in this method, as in the other two methods, the bars are sheared to length cold, hot shearing being impracticable, and hot or cold sawing too expensive.

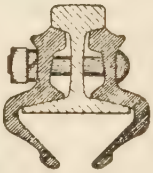


Continuous Rail Joint.



Weber Rail Joint

Duquesne Rail Joint.

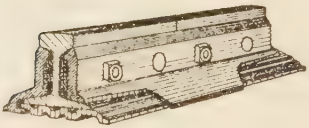


100 Per Cent. Rail Joint.

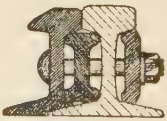
Reinforced Angle Bar,
Latest Type of Rail Joint.

Duquesne and 100 Per Cent. Joint.

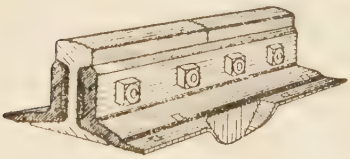
Hatfield Rail Joint.



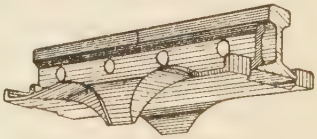
Wolhaupter Rail Joint.



Barschall Rail Joint.



Q & C Bonzano Rail Joint.

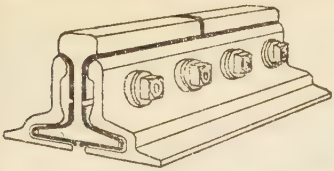


Abbott Rail Joint.

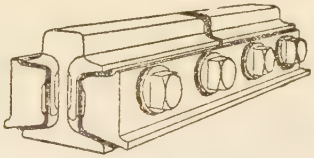
Williams Reinforced Rail Joint.

Atlas Rail Joint.

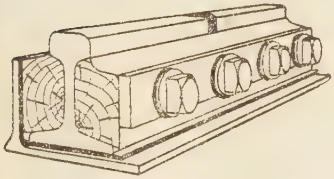
FIG. 161. Sketches showing some of the different types of Rail Joints used during the last 20 years.



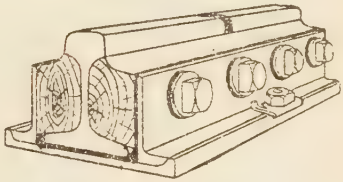
Continuous Insulated Rail Joints.



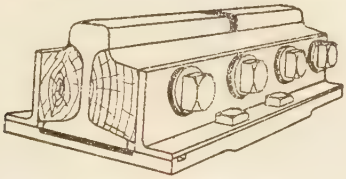
Keystone Insulated Rail Joint.



Weber Insulated Rail Joint.



Braddock Insulated Rail Joint.



O'Brien Insulated Rail Joint.

FIG. 162. Types of Insulating Rail Joints. The heavy black lines represent insulating fiber.

Heat Treatment of Rail Joints: It will be noted that the hot worked oil quenched bar is at present the only representative of heat treated rail joints. Of course, other methods of treatment, such as quenching in water and tempering, could be used, but oil is preferable because it protects the material from rust and eliminates the necessity for annealing or tempering after quenching, the quenching in oil giving about the same results as a low temperature tempering after quenching in water. As to the desirability of reheating the bars after the hot working, there is no reason to follow such a procedure, because the operations of punching, notching and straightening can, with proper equipment, be done in less than two minutes, and the time required for these operations can be made very uniform, so that, by heating the bars only a few degrees (20 to 40 degrees) above the temperature desired for quenching, each bar can be punched, notched, and straightened if necessary, and still be delivered to the oil bath at the proper temperature for quenching. Therefore, it is doubtful if additional benefits, provided suitable equipment is employed for properly handling the bars as described above, are to be derived from more refined methods of treatment, and certainly, the gain would not be commensurate with the additional expense involved in applying such treatments. A similar statement may be made in regard to the annealed bar, when it is compared with the cold worked untreated bar. Ordinarily, only light weight splice bars are now cold worked, and

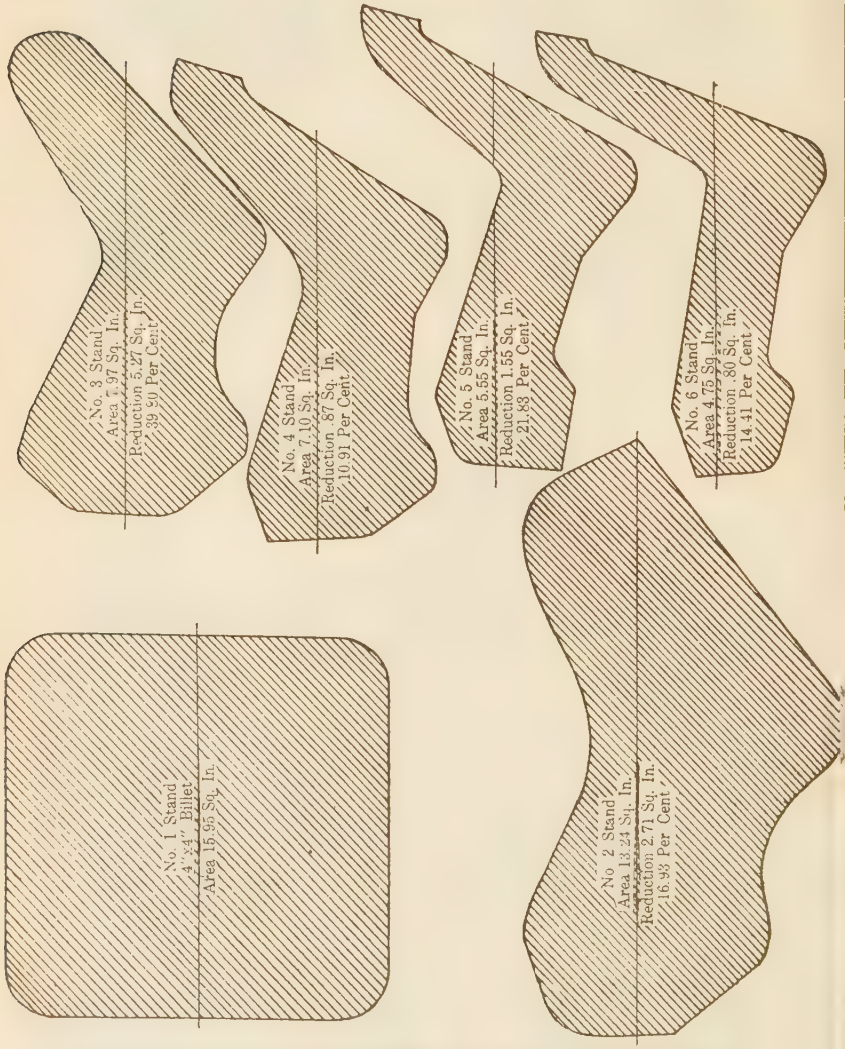


FIG. 163. Passes for Rolling a Light Splice Bar, or Common Angle Bar.

practically all splice bars for 90-pound rails, and heavier, are hot worked, these heavier joints being too thick and hard to be punched cold. If the bar is heavy enough or hard enough to be seriously injured by cold working, a subsequent annealing will not remove or entirely heal the defects. Also, while annealing may make the bar more ductile, it also softens it, and, since strength combined with fair ductility are the properties most desired in rail joints, annealed bars fail to meet the requirements of a good rail joint. These statements agree with the results obtained in actual practice. A few years ago, during the development of the heat treated rail joint, cold working followed by annealing was quite frequently employed, but the practice has now been wholly abandoned.

The Edgar Thomson Splice Bar Shop is fully equipped to finish practically any type of rail joint by any one of the approved methods cited above. To expedite the handling of the bars, the shop is divided into a number of continuous units. Each unit is provided with a cold shear for cutting the bars to length, a reheating furnace for heating prior to hot working, a punching machine for punching the bolt holes, a similar machine for notching the bars, a press for straightening them, and an oil tank for quenching. All these appliances are arranged in a series and in the order given, so that each bar may be passed easily and quickly from one to the other. The punchers and press are set close to the delivery end of the reheating furnace, but for safety reasons, the oil tanks are placed in a separate building and are about 20 feet from the straightener. An endless chain running at a uniform speed is employed to carry the bars from the straightener to the oil tank. Here this chain drops the bars either into the oil tank or upon another chain which extends at right angles to the first and is used to carry cold-or hot-worked bars to the shipping platform. For controlling the temperature of hot worked and oil quenched bars the furnaces are equipped with pyrometers, and in the case of oil quenched bars the temperature is frequently checked just before the bars enter the oil bath by means of an ardometer. Further details concerning each method of working will be found in the following paragraphs.

Cold Worked Bars: In this method the order of working is this: First, the bars are sheared to length, inspected for straightness and flaws, straightened, if necessary, punched and slotted. The dies on the shears are, in all cases, made to conform exactly to the shape of the bars, so that a nice clean cut is made without in any way deforming the bar. However, in shearing the continuous joint, a slight bending of the outer edge at one end is unavoidable. For a similar reason, the bottom blocks, or dies, of the punching and notching machine support the web while the punches descend from above, pushing the material through conforming openings in the blocks. All dies are made of the highest grade of special tool steels and are kept in the best possible condition. In this way the hole is made as smooth as it is possible to make it by punching. It is evident that it is a great advantage to the shop to have the bolt holes on each bar alternately round and oval rather than all oval or all round, for in the latter case only every other bar could be punched on one arrangement of the dies, and the bars would require careful matching. As to the effect of cold working, it is quite clear that the bars of low carbon content, under .28 per cent. carbon, soon recover from the effects of the working, but in the higher carbon bars these effects are permanent and may do injury to the bar. On the entering

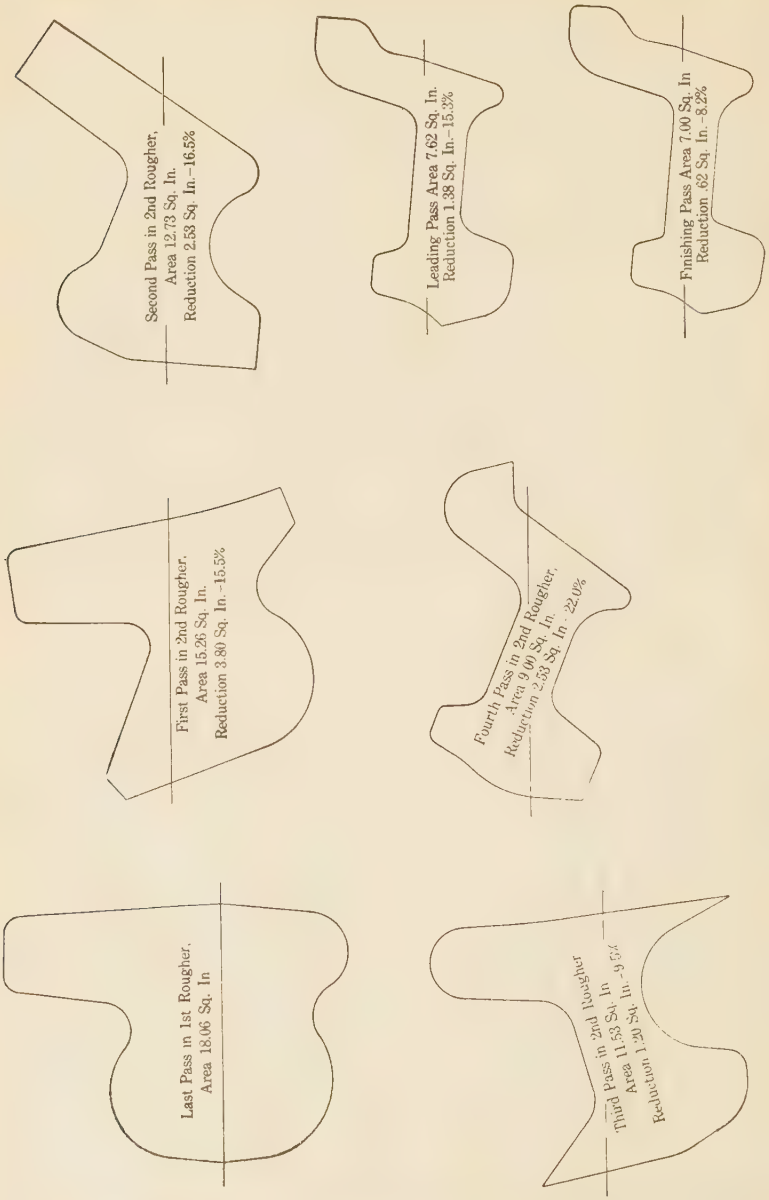

Second Pass in 2nd Rougher,
Area 12.73 Sq. In.
Reduction 2.53 Sq. In.–16.5%
Leading Pass Area 7.62 Sq. In.
Reduction 1.38 Sq. In.–15.3%
Finishing Pass Area 7.00 Sq. In
Reduction .62 Sq. In.–8.2%
First Pass in 2nd Rougher,
Area 15.26 Sq. In.
Reduction 3.80 Sq. In.–15.5%
Fourth Pass in 2nd Rougher,
Area 9.00 Sq. In.
Reduction 2.53 Sq. In.–22.0%
Last Pass in 1st Rougher,
Area 18.06 Sq. In
Third Pass in 2nd Rougher
Area 11.53 Sq. In
Reduction 1.20 Sq. In.–9.5%

FIG. 164. Last Seven Passes for Rolling a certain Heavy Rail Joint—Illustrating the Rolling of Reinforced Angle Bar Sections.

side of the punches the metal is compressed beyond its ultimate strength, while the material on the opposite side is put under a tension, as may be observed by an examination of any hole made by punching. One of the direct results of this cold working is to increase the hardness of the metal about the hole, but the worse effect, which applies only to high carbon bars, is found in the very small cracks which extend into the metal along lines perpendicular to the surface of the hole. For these reasons, cold working is the most objectionable of all the methods cited. The difficulties, as well as the evil effects of cold working, increase as the carbon content of the steel increases. Hence, only low carbon bars (below .28% C.) should be cold worked. As a rule, the method is applied to the smaller angle bars and fish plates.

Hot Worked Bars: In hot working angle bars, the order of procedure is as follows: Shearing to length, heating, punching, notching, straightening, if necessary, and cooling. Patented bars, of course, may require additional operations. In hot punching any bar, in order to avoid spreading of the metal and consequent distortion of the bar, it is necessary to employ a confining die, that is, the cutting die must be enclosed in a die block or frame, the upper surface of which, together with the die itself, conforms in shape to the inside surface of the bar. Hot worked bars must, therefore, be punched from the outside, or inward. Most cold worked bars may be punched from the inside, or outward, as there is no danger of spreading the metal, and enclosed dies are not necessary. The straightening machines are presses provided with a set of dies for each size of each section. One die conforms to the size and shape of one side of the section and the second die to the other side, and both are set in the press so that at the end of the stroke the space between the dies is of the same shape as the bar and just equal to it in thickness. The furnaces employed for hot working are of the continuous type. They are rectangular in shape and wide enough to admit two rows of bars laid end to end. Natural or coke oven gas is the fuel used. In order to obtain an even distribution of the heat, the furnace is provided with four ports, and in addition four large burners of the Bunsen type are located at the bottom along each side of the furnace to supply heat under the bars. Recording pyrometers are employed, so the exact temperature of the furnace may be ascertained at any time. After being sheared to length, the cold bars are laid upon water cooled skid pipes and pushed into the furnace from the rear by means of electrically operated dogs. The length of the furnace and rate of charging is such that about two hours are consumed in pushing each bar through the furnace, this time being sufficient to bring the bar to the working temperature of about 800° to 830° C., which is a little higher than necessary for working, as the temperature drops by the time the bar reaches the machine to 790° or 815°. The skids end near the front of the furnace, and the bars descend to a hearth, whence they are removed with tongs through doors. Needless to say, the bad effects of cold working are entirely avoided by hot working, and in addition the reheating to a point just above the critical, or transformation, range tends to refine the grain structure and make it more uniform. But the bar is neither hardened nor toughened by the process, so practically all railroads are using a .40 to .50-per cent. carbon, oil quenched angle bar of some special design, which has the advantage of simplicity combined with great toughness, or ductility and strength.

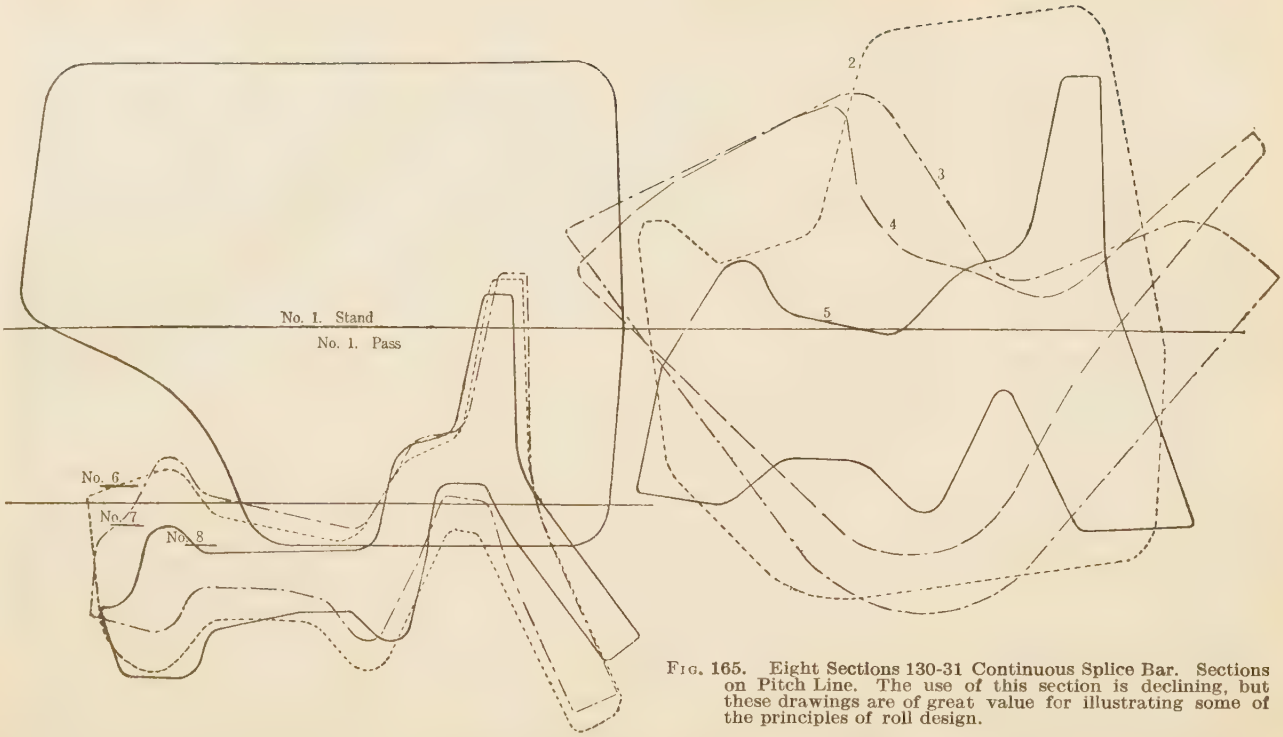


FIG. 165. Eight Sections 130-31 Continuous Splice Bar. Sections on Pitch Line. The use of this section is declining, but these drawings are of great value for illustrating some of the principles of roll design.

Hot Worked and Oil Quenched: In this method, not only are the evils of cold working avoided, but the strength and ductility, or toughness, of the bars are much improved, also. The method, which is especially applicable to high carbon angle bars, consists in hot working the bars in the usual way and quenching them in oil before they have cooled to a temperature below that of the critical range. The necessity of completing the work before the temperature drops below this point may require the bar to be heated to 30° or 40° C. higher than for ordinary hot working, and permits no delay in the operation. The exact temperature in each case depends on the composition of the steel, the size of the section, and the mechanical properties desired. For quenching the bars, a continuous oil tank in close proximity to the presses is provided. The tank is rectangular in shape and provided with a linked belt conveyor, which slowly carries the bars through the oil, the speed of the belt and its direction of travel being so regulated that the bars, upon entering at one end of the tank, are carried down into the oil, across the tank, and up to the opposite end and are cooled to 70° C. or less. The oil used is a special grade of petroleum product that will not get viscous and has the most favorable cooling properties. In order to keep it cooled to the proper temperature, the oil from the quenching tank is pumped through a set of water cooled pipes and into a large storage tank. The fresh oil for the quenching tank is pumped from the bottom of this tank. By means of this circulating system the temperature of the oil is kept, usually, at about 60° C. The temperature of the oil is taken at intervals of an hour or so to make sure its temperature does not rise too high.

SECTION III.

STRUCTURAL AND OTHER SHAPES.

Plan of Study: It is needless to remark that a detailed description of the rolling of each of the many sections included under this heading would result in a very lengthy discussion, and it is doubtful if such a discussion would prove to be of much value in accomplishing the ends at which this book aims. Besides, while the rolling of each shape or section presents difficulties peculiar to itself alone, there are certain problems common to all sections, and of these general features an example has already been given in the description of the rolling of rails. Unlike rail mills, structural shape mills vary much, both in type and equipment, and often the methods for rolling a given section must be adapted to the mill conditions. In general, the size of the section, for economic reasons, will determine the size of the mill, and the different sizes of the same section will be rolled on different mills. No one mill, therefore, can be selected as an example of the rolling of even one of these shapes. For these reasons a brief and more or less general discussion of the different roll designs for some of the more common sections is all that will be attempted here, and it is hoped the study will be found both interesting and profitable.

Angles: Among the first shapes to be rolled was the angle. Three methods of rolling this shape have been developed. In two of these methods the forming of the angle is begun from a rectangular bloom, or if the bloom is square, from a rectangular roughing pass in the mill. In what is known as the butterfly method, the grooves are so designed that each successive pass from the slab approaches the right angle of the finished bar, the piece being gradually bent and reduced at the same time. In the second method, which may be called the flat-and-edging method, the legs are kept flat until the leader and finishing passes, when they are bent to form a right angle. In the third method, the forming of the angle is begun from a rectangular bloom by first working off one corner and then recessing it till the desired thickness of the legs is obtained, but this method is now seldom used.

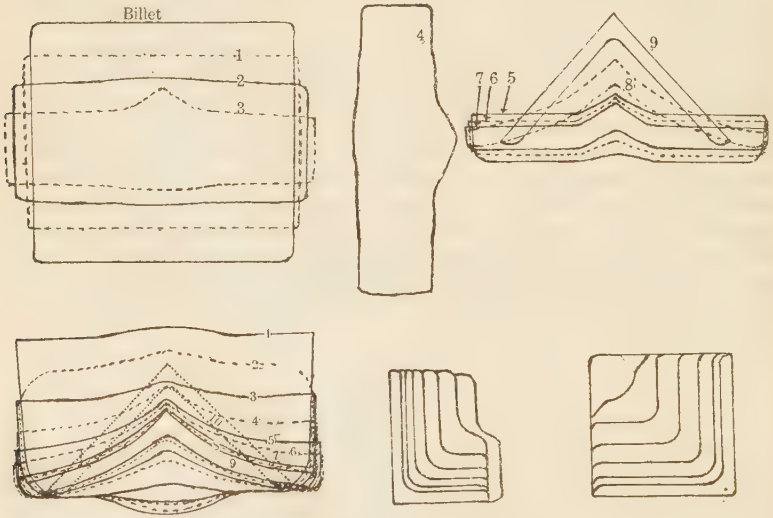
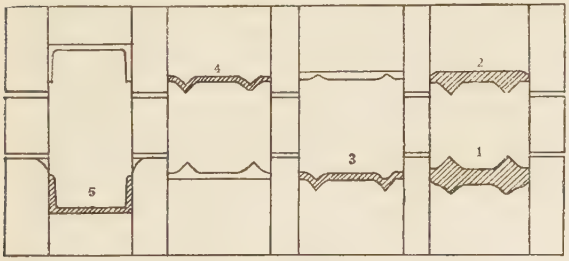
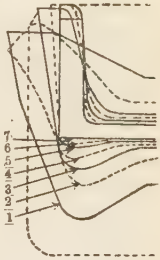


FIG. 166. Methods of Rolling Angles.

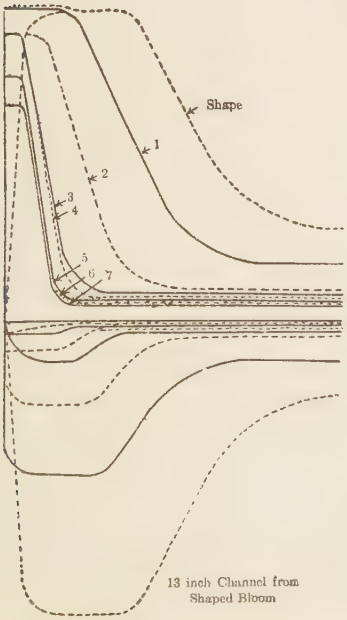
The Three Methods Compared: The part of the angle that gives the most trouble in rolling is the back and the apex, which must be square and sharp. As shown in the accompanying sketches, this difficulty is overcome in the first and second methods by reserving metal in the first passes on both sides of the bar where the apex is to be formed. In the last passes this excess metal is available to fill out what would be lacking on account of the bending, which tends to draw the metal down from the apex. In the third method the apex and back are perfect from the beginning. As to the relative merits of the three methods, there is, of course, much difference of opinion. However, there are two features about the second method that appears to a decided advantage when compared with either of the other two. The ability to employ an edging pass so near the finishing

to control the width makes it possible to reduce the piece rapidly in the roughing passes and so cut down the total number of passes required to form the section. Then, too, since nearly all the work on the section is done in the flat passes, the difficulties encountered when deep grooves are used in the rolls are entirely avoided. Usually angles are formed in from nine to eleven passes.





Butterfly Method for Channels as first designed



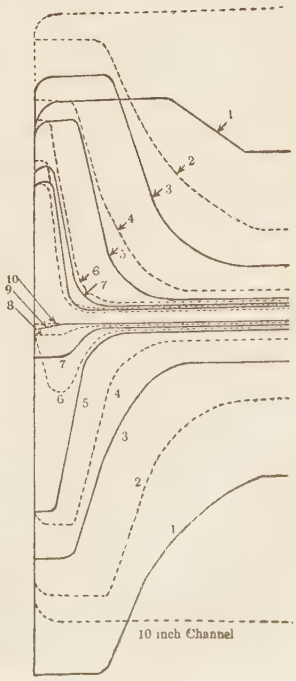


Fig. 167. Methods of Rolling Channels.

The Channel: Channels are rolled by two distinct methods known as the butterfly and beam roughing methods. The butterfly method is said to have originated in the year 1873 at the Upper Union Mills of Carnegie, Kloman & Co., and is sometimes called the slabbing method. In being formed by this method, the section resembles that formed by two angles rolled side by side in one set of grooves, and by the same butterfly method. In the second method the bloom, in the rectangular form, is edged for the first pass and is then worked down from each edge or face alternately by grooves in the roughing passes until it much resembles a beam, and in reality it is a beam in the rough. Succeeding passes, however, work off the flanges on one side of the web. The function of these temporary flanges is to supply metal for holding the height of the flanges on the opposite side, thus forming a channel with full sharp edges and square sides. This method is said to have an advantage over the butterfly method in that the roughing rolls may be used either for beams or channels and a greater number of weights may be taken from the same set of rolls. In rolling deep channels the butterfly method would appear to overcome the difficulty of making the flanges nicely, but more roll space is required than in the beam roughing method, and since the great width of the section makes edging impracticable, it is more difficult to secure well formed edges on large channels. In the beam method, the butterfly idea is used to some extent, and in order to obtain the proper height and thickness of flange readily, the flanges are rolled at an angle to the web and finally bent to right angles in the leader and finishing pass in the same way, though to less degree, as in the butterfly method. For channels, about the same number of passes is required as for angles. Very large channels are often rolled from shaped blooms, as in the structural mills at Homestead, which work in conjunction with a blooming mill and a roughing mill to roll large beams and channels. The blooms for both these shapes have much the same form, the channels being finished by the beam-rougher method.

Beams, Ties, and Piling: Beams were, doubtless, first made by riveting a plate and four angle bars together, then later by bolting or riveting two channels together back to back. Up until 1895 they were considered very difficult sections to roll, but the great demand for these shapes during the succeeding years so stimulated thought in their manufacture that most of the former difficulties have been overcome, and standard beams are now rolled with as little trouble as angles, channels, or rails. Indeed, the rolling of these sections very much resembles that of rails, for if the head of the rail be replaced by a flange the sections would be practically the same. Like rails, there are, in the case of grooved rolls, two methods of rolling beams, namely, the flat, or slab-and-edging, method and the diagonal. But unlike rails, the diagonal method for beams is far superior to the older flat method, because the oblique design of the passes makes it possible to secure a much greater length of flange than was ever produced by the first method. This advantage is forcibly illustrated in

the steel tie section, the rolling of which was first successfully accomplished at Homestead. This section with its very thin flange, which has almost no taper, would have been looked upon, fifteen years ago, as an impossibility from a rolling standpoint, and is considered one of the greatest achievements in roll design. The largest beams are best rolled from shaped blooms in a special mill provided with both horizontal and vertical rolls, the former bearing on the web and the inside of the flanges

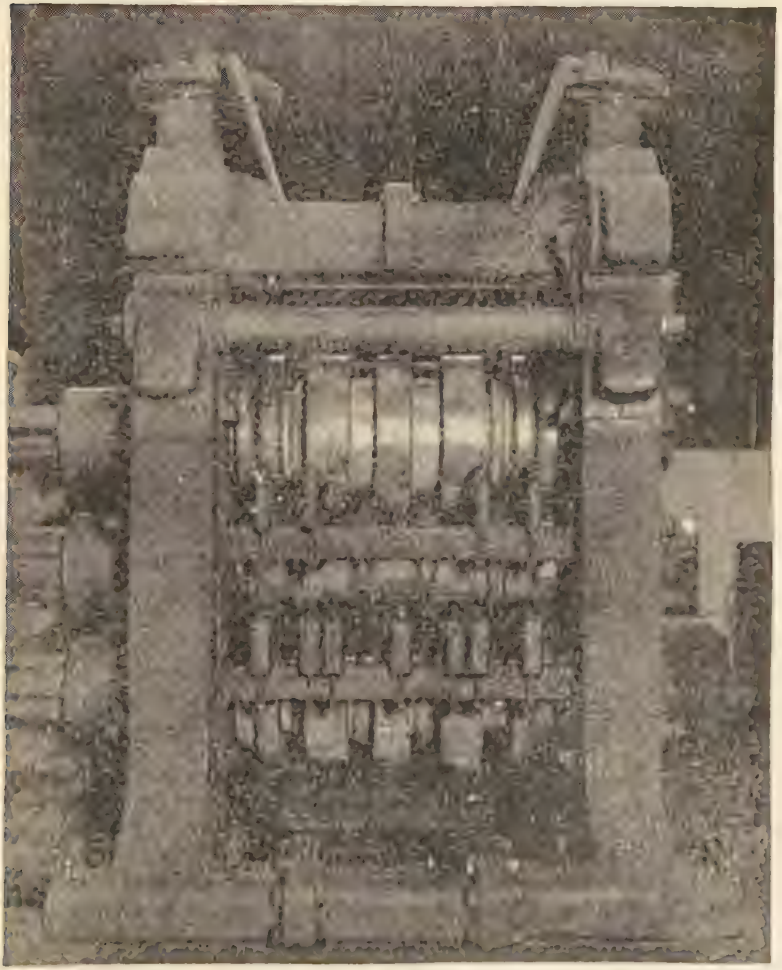


FIG. 168. Roughing Stand of a 24-inch 3-high Structural Mill, showing rolls designed for beams.

and the latter on the outside of the flanges. U. S. steel piling is another section which much resembles the rail in rolling. Here, the ball and web of the piling, as finished, is almost a duplicate of the head and web of the rail, and the remainder is rolled as a flange up to the leading and finishing passes, when the two halves or legs are bent down to form the socket for the interlock. It is rolled either by the flat or diagonal methods.

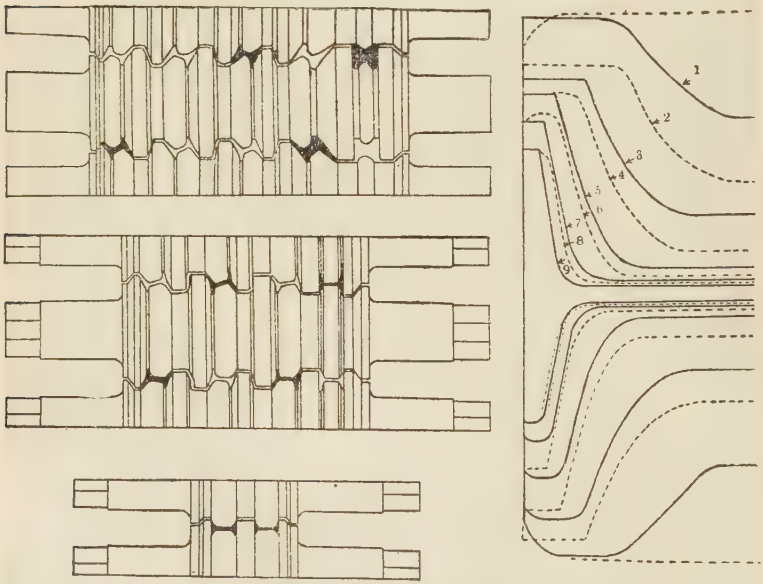


Fig. 169. Methods of Rolling Beams in Grooved Rolls.

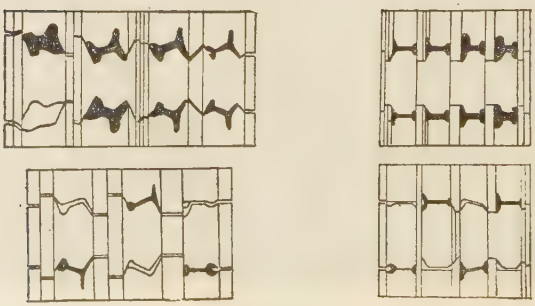


Fig. 170. Methods of Rolling Piling.

Zees and Tees: Zees may be looked upon as double angles or channels with reversed legs, or flanges, and the methods of rolling correspond to the first two methods for angles. As to tees, it is doubtful if any other section offers as little opportunity for variation. There is only one way by which the tee can be rolled. In this method the shaping begins from a square billet or bloom. One side of the square is retained to form the base, or table, of the tee, while the edges of the opposite side are both recessed in the first forming pass by collars on each side of a groove into which part of the metal flows to start the stem. The piece is then edged for the next pass, in which the stem is reduced between the flat surfaces of the rolls, while the two parts of the table pass through grooves in the two rolls. In the next pass the piece is turned with the stem up, which will pass through an idle groove, while the table on each side of the stem will be reduced between the plain surfaces of the rolls. This process is then repeated, the piece being worked alternately on the stem and table, until the section reaches the size desired in the finishing pass. Usually, in this last pass the stem is in the groove of the lower roll and the table is reduced between the rolls. In order to prevent the bar from following the roll on the delivery side, this groove, as for all the idle grooves, must taper slightly from the top and be large enough to give easy passage for the stem, thus making it somewhat wider than the stem is thick. The reduction of the table then results in the formation of a slight overfill at the base of the stem. This bit of excess metal cannot be removed, because the stem was necessarily finished in the preceding, or leading, pass. If the section were finished by working on the stem, the same defect would be developed.

Finishing Sections: Most shape mills are provided with hot saws located after the finishing pass and near the cooling beds. These saws are intended mainly for cutting test pieces, but in some mills they are used for cutting off crop ends or dividing mill lengths where the cooling beds are too short to take full mill lengths. The test pieces are of two kinds, namely, those for the roller, whose duty it is to see that the section is rolled to the correct dimensions and weight, and those for the physical laboratories. With these exceptions, however, the full mill length is sent directly to the cooling bed. Here, as in the case of rails, the cooling causes the shapes to bend considerably, and cold straightening is necessary. For this purpose, the piece is next passed through a cold roll straightening machine, and if necessary through a gag press. The roll straightener is capable of straightening in one direction only, so that if, through handling or other cause, the piece has been twisted or bent laterally, it can be made straight, in all directions, only by using a gag press after the roll straightener. From the straighteners the material passes the cutting machines, which, in order to keep up with the mill, must be either shears or cold saws. For this reason, exact cutting to length is out of the question, and a liberal cutting tolerance is always desired by the mill. As a rule, angles, zees and small tees are sheared, while channels, beams and large tees are cut with cold

saws. During the cutting, any pieces that contain noticeable defects are discarded and cut into scrap lengths, and, after the cutting, the material is subjected to a very rigid inspection for the more minute surface defects.

Rounds: In the steel business, rounds are often designated as **hand rounds** or **guide rounds,** and these terms are indicative of the two methods for rolling these shapes. In the first method, the bloom or billet is first reduced in diamond shaped roughing passes to the form of a round cornered square. Then, by means of tongs in the hands of the workmen, this square

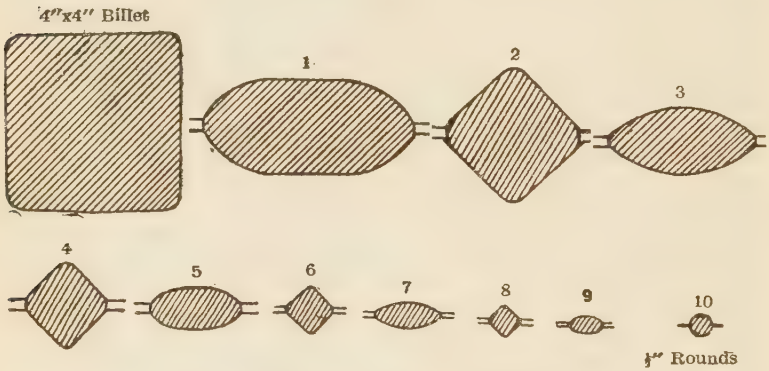


FIG. 171. Rolling a Half-Inch Guide Round.

is supported in the correct positions and passed through a single round-forming, oval-shaped pass, or two similar round-forming passes, until it has been worked into the round form, which can be accomplished by turning the piece through an angle of 90° after each pass through the rolls. From three to five passes in the finishing stand are required to form the round by this method of rolling. In the case of guide rounds, the size of the billet may be reduced in the roughing passes in a manner similar to that for hand rounds, or by any other method that will give a round cornered square. This square is then reduced in one or two passes to an oval, which is then edged, and while supported in this position by a guide, it is put through a round finishing pass. The compression in this pass shortens the long axis, while the spreading of the metal lengthens the short axis of the oval to equal the radii of the round. In a general way, large rounds, that is, those over two inches in diameter, are rolled by hand, while small rounds, less than two inches in diameter, are rolled with guides, but there is a narrow range from about one and three-fourths inches to two and one-half inches where either method may be employed. Regarding the relative merits of these two methods, hand rounds are by many preferred to guide rounds where great accuracy and uniformity in diameter are required. However, guide rounds are now rolled with a high degree of accuracy, and

since the uniformity and accuracy of the hand rounds depends on the skill of the workmen, it is doubtful whether equal care and attention applied to both methods would leave, on the average, much wherewith to choose between them.

Cutting and Straightening Rounds: In order to keep up with the mills, rounds are either hot sawed or cold sheared to convenient lengths, and neither method is at all exact. Hence, in these lengths, either single or multiples of those desired, proper allowance must be made for the exact cutting, which is performed by special cutting machines after the round is straightened. The straightening may be done either on the gag press or on special straightening machines, called from the inventors the Brightman and Abramsen straighteners. The Brightman consists of two rows, or sets, of concave rolls mounted upon opposite sides of a revolving frame, so that, with their axis of rotation at an angle to that of the frame, the concave surfaces of opposite rolls bear on the round and grip it in such a manner as to force the bar along longitudinally and at the same time bend it at the crooked places enough to straighten it. In the other type of machine the rolls are mounted on a stationary frame, while the piece itself is revolved and forced through it. The straightening develops one serious defect, which renders the bar unsuitable for some purposes. The scale in the spiral path of the rolls is rolled into the surface, causing a slight pitting, which can be removed only by machining.

Flats: Because they are the simplest, the flats were the first sections to be rolled. The main problem involved in designing the rolls for flats is the control of the width, which is done in two ways after the piece has left the roughing rolls. The first method, called the **flat and edging,** consists merely of rolling the piece on edge at intervals in deep grooves cut in the rolls. The other method of controlling the width lies in the use of the tongue and groove passes as described under the rolling of sheet bars, and is best suited to the rolling of thin material. In this method the last two passes will be between plain rolls, while in the flat and edging method the planisher will be an edging pass. It is in this pass of the flat and edging method that the three different edges on flats are formed. Thus, if the bottom of the groove is flat, a common swell or oval edge will be formed by the spreading of the material in the center, which is hotter than the outside; but if the base of this groove is made sufficiently concave, the edge of the bar will be round; if convex, a square edge will be formed. In the eighteen-inch mill at Clairton there is used, next to the finishing pass, a set of vertical rolls, which eliminates the difficulty of rolling a wide thin flat in an ordinary groove.

Hexagons: There are two methods used for rolling hexagons. By one method all six corners are formed in the rolls, three in the top and three in the bottom. The clearance between the rolls in this case comes on opposite

flat surfaces of the bar. In this manner of rolling, the corners of the hexagon cannot pinch out. Hexagons rolled thus are best suited for cold drawing purposes, as they will be free from pinches which draw out into laps. In this method, the first pass in the strand, or first former, is a square which has been broken down from the billet in the roughing and pony roughing stands. The square is then put into the second strand, or former, and comes out in the form of a six-sided flat, the two widest sides of which are convex. The bar is then edged into the leading or planishing pass, where a reduction of about 25 per cent. takes place, in the case of small hexagons. The bar coming out of this pass has six sides as before but has two of its corners formed by the clearance of the rolls. The top and bottom sides are slightly concave to allow for the spread as the bar is edged into the finishing. Here the bar is given a light draft, in order to square it up, the reduction being only 8 to 10 per cent. In the other method, two of the corners of the finished bar are formed at the clearance of the rolls, hence care must be taken to keep these corners from pinching out. The bar coming out of the planishing in this method, is in the same position as the finished bar of the first method. The bar is turned 90° and entered into the finishing, so that its top and bottom surfaces are flat or horizontal and two of its corners are in the clearance between the rolls. In the one method, but three passes are required to form the finished bar from the square, while the other method requires four.

Deformed Bars: This term is meant to include any bar having an irregular surface or a surface on which there are projections or depressions, such as the various concrete reinforcing bars, clip iron, hame strap, etc. Some of these bars are so complex as to excite the highest admiration and astonishment from those not familiar with their manufacture. While they require the greatest ingenuity on the part of the roll designer, they are, however, produced with less difficulty than might be supposed. Briefly, the secret of their formation consists in first working the metal down through the ordinary passes to one of the common forms, such as a flat, square, round, or oval, whichever is best for forming the bar desired, and then putting it through one or two deforming grooves containing the necessary recesses or elevations. It is here the chief trouble occurs. As the deformations must be made in the finishing pass, or the leader and finishing combined, a heavy draught in these passes is necessary, and the metal is usually, even with the fastest working, at a very low temperature for working These conditions put a heavy strain on the mill, and, owing to the lack of plasticity in the metal, the projections will not fill out easily. In order to avoid vibrations which cause the bar to slip in passing through the rolls, thus causing the deformations to be made at irregular intervals, mills rolling these sections are provided with separately driven finishing stands.

CHAPTER IX.

THE ROLLING OF STRIP AND MERCHANT MILL PRODUCTS

SECTION I.

STRIP, OR HOOP, MILLS AND THEIR PRODUCTS.

Meaning of the Word Hoop: As originally applied, the word hoop meant that light narrow material which, cut into short lengths, was used to bind casks, barrels, buckets, and the like, but as now employed the word is a class name that stands for a large number of products. The Carnegie Steel Company, for instance, uses the term to cover all materials from 13 gauge to the thinnest material rolled on their mills, and from three-eighths inch to eight and five-eighths inches in width. This range covers material used for a great variety of purposes in addition to hoop, such as skelp for tubes, blades for knives, and blanks for stamping hundreds of hardware specialties, a class of material that represents a little better grade of steel than ordinary hoop. In a way, this use of the word hoop is unfortunate, especially as a more suitable class name is supplied by the term strip. With strip for a class name, hoop would have retained its original meaning, for which there is no substitute, and all danger of ambiguity would have been avoided.

Hoop as a Rolling Specialty: Being, perhaps, the largest producer of strip in the country, the Carnegie Steel Company's mills furnish the best example of the equipment and organization required to roll this class of material. A specialty mill is not a mill that rolls a specialty nor a variety of specialties, but one that has specialized in the rolling of a single product. According to this definition, and using the term hoop in its broad sense as outlined in the preceding paragraph, the hoop mills of this company are best described as specialized specialty mills, because they are laid down, not for the general purpose of rolling hoop or strip, but in such a manner that each mill is designed and equipped to roll a certain kind or grade of strip. The advantage of such a system is at once evident, making it possible for the mills to meet the many demands of the trade most readily. Thus, they are able to give accuracy, where accuracy is required; finish, where finish is desired; quantity, where quantity is the main consideration; and all with a better quality to the customer and at a greater saving to the producer than would be possible in any other way.

The Carnegie Hoop Mills: From what has just been said, it will readily be surmised that the hoop mills of this company are many in number and of various types, and no detailed description of all of them can be

expected. This excuse will be better appreciated when it is known that among their many strip mills at least six types, or designs, of mill are represented. However, these mills present certain features of a general nature, for the omission of which no valid excuse can be found. In size their hoop mills range from seven to twelve inches, the most common size being eight and ten inches. In some of the mills the different stands of rolls will vary in size. Thus in the McCutcheon No. 6 Mill, eleven-inch rolls are employed in the roughing stands, nine-inch in the intermediates, and eight-inch in the planisher and finisher. The rolls may be of different sizes in the same stand, also, as will be explained later. As to the materials of which the rolls are made, the roughing rolls may be of steel and the intermediates of cast iron or adamite, but the finishing rolls are always of the hardest chilled iron. The number of stands in these mills vary from eight to twelve per mill, and their arrangement is such as to produce the kind of hoop desired to best advantage, as will be more clearly explained later.

Methods of Rolling Hoop: While hoop of the heavier and medium gauges and narrower widths is successfully rolled by the flat and edging method, it is readily understood that this method is not applicable to all sizes of hoop. After the material leaves the roughing rolls there is but one way remaining, then, by which it can be reduced, and that is by the tongue and groove method already described. These tongue and groove passes will be found to be three or four in number, though only two are used in some of the mills, and to be followed by two or three stands of plain rolls. As to the manner of breaking down in the roughing stands, there are two methods of rolling—one in which the billet is reduced by flat and edging passes and another in which the roughing passes are ovals and squares. The latter method gives a more rapid reduction, and will be employed usually where only two roughing stands precede the tongue and groove rolls.

Precautions Required in Rolling Hoop: The chief difficulty encountered in rolling this light strip lies in getting the hoop through the rolls before it becomes too cold to roll, or in keeping the temperature uniform at the finishing roll, which is necessary to produce a strip uniform in gauge. Considering the rapidity with which the metal is cooled on account of the thin section and the chilling effect of the cold rolls, the accuracy as to gauge and width maintained by the hoop mills is little short of astonishing. In this case the ingenuity of the engineer who builds the mill and that of the roll turner who designs the rolls are both required, in addition to the skill of the rollers, to produce the desired result. By reducing the number of passes to a minimum in the ways already described, the roll designer has done his bit, but even then the last end of a long strip will be cooled to a temperature so much lower than the first that it will finish several thousandths of an inch thicker, unless the mill is adapted to rolling it. These drawbacks are overcome by a combination of ingenious

schemes. First, the mill is run at as high a speed as practicable. Second, it is arranged and operated so that as little time as possible intervenes between passes. Thus, in the more modern hoop mills, roughing rolls on the continuous plan are used, and these are placed very close to the furnace, whence the billet, being at once reduced in the two or three roughing passes, passes over roll tables to the tongue and groove rolls, which are arranged on the continuous plan or in train. If the latter plan is followed, mechanical repeaters are employed for short lengths, or the piece is looped from pass to pass by hand, by which means it may be rolling in two or more stands at one time. In order to avoid having the loop, which increases with the length of the piece, run far out on the floor, and thus become chilled, each pass following the tongue and groove passes is made to run as much faster as its predecessor as is necessary to take up the slack due to the elongation. Other schemes to equalize the finishing temperature are also employed. It is said that at some hoop mills the end of the billet which represents the last end of the hoop to pass through the rolls is heated to a higher temperature than the first end. In the 10-inch continuous mill at Youngstown, where the strips are about 1800 feet in length, one end of the billet will be in the furnace, while the other will be coiling some 200 feet away at the other end of the mill as finished strip. Other factors affecting the uniformity of gauge, or thickness, are the wear of the rolls and the bearings. To overcome the wear of the former, which also affects the finish, the path of the piece through the leading and finishing passes is moved over to a new surface about every twenty minutes, or whenever these surfaces become too rough. The vibration of the mill pinions produces waves or slip marks on the surface, if the last stands are in train with the tongue and groove rolls, hence the planishing and finishing rolls are generally separately driven in mills rolling the best grades of hoop, and only one of the rolls is driven, the other revolving by friction due to contact with the driven roll. The planisher may be in train with the tongue and groove rolls, but the finishing stand is almost always separately driven. At some of the mills where the finisher or planisher, or both, is in train with the rest of the stands, the bottom roll is much larger in diameter than the top roll or the rest of the mill, and is driven, while the top roll revolves by friction. The larger diameter of the bottom roll increases the speed of delivery of the stand. The finish on some hoop is of great importance. To provide for this requirement, scrapers are employed in front of the chill, or finishing, rolls. These scrapers consist of two horizontal bars spaced about eight inches apart and fixed parallel to and just in front of the rolls, and of two other bars similarly arranged but fastened to the two prongs of a fork that can be moved up and down by means of a lever. In this way the movable bars can be lowered as desired into the spaces between the fixed bars and the rolls. As soon as the rolls grip the piece the scraper is brought into action, and the piece is bent sharply up and down over its edges, thus cracking the scale and removing it at once. As the piece, after coming out of the finishing pass, is near or below the critical

temperature, no more scale is formed, and a smooth bluish surface results. About five or six feet of hoop on the front end is not thus scraped, because the great speed of the piece carries it through this distance before the scraper can be brought into play. In order to eliminate this unfinished end with as little waste as possible the shears are located, preferably, at the mill end of the cooling bed, so that this end of the strip is the last to be cut. The adjustment of the rolls is also an important matter in rolling hoop. To illustrate this point, if one of the finishing rolls is enough out of level to make a difference of only one-ten-thousandth of an inch in the thickness of the hoop on its edges, it will bend toward the heavy side in leaving the pass an amount equal to one foot in thirty feet of length. As the stiffness of an ordinary hoop is only sufficient to push it, even on a very smooth run out, a distance of about thirty feet, some means of cheaply delivering the strip away from the last stand of rolls must be used. In Carnegie mills, this delivery is accomplished in three ways, namely, by hot coilers, by conveyor belts in the runouts, or by pneumatic runouts. In the last named type of conveyor, air blown at high pressure through holes in the bottom of the runout and at angles directed away from the mill, lifts the strip, decreases the friction and helps to carry it along.

Finishing Hoop: Hoop may be finished in many ways. As to the cutting of hoop, it is always cold sheared, and this may be done so as to give either both ends square or one end square and one end round. For this kind of cutting, a special die with a double edge, one round, the other square, is used, and the shapes on the ends of the hoop are formed by punching out a small part of the hoop. Ordinary hoop, not coiled, is cut on alligator or small guillotine shears, but some continuous mills are equipped with automatic shears, which consists of two revolving wheels on each of which a shear knife is mounted. By regulating the relative speeds of the wheels, these shear-blades are brought together in every so many revolutions, so that, as the strip is fed into the shear at a definite speed, it is cut into approximately equal lengths. Anything near exact cutting is impossible on this machine, due to slipping of the belts and the play in the parts of the machine. Flaring and punching machines are provided at some of the mills, and in this connection it is to be remembered that the flare on a hoop is measured correctly by one-half the difference between the largest and smallest diameters. All three methods of bundling, in strips, in scrolls and in coils, are practiced. As to coils, some of the mills can coil in multiple or single strips, while others can coil only in singles. Hot coiling can be done only at certain mills, also. It is a matter of pride with the men at the mills to turn out the finest product, and any order that calls for extra quality and finish is sure to receive the attention it deserves. On such material, special tests, such as the acid test for scale pits and bending over tests for seams, are often made in addition to the ordinary inspection for surface defects and gauging for thickness and width.

SECTION II.

MERCHANT MILLS.

What the Merchant Mill Is: The first mills were what we of to-day would call merchant mills, though the term was perhaps not then applied to them. In the beginning of the industry, all mills doubtless rolled a variety of simple sections such as rounds, squares, flats, etc., but as the business grew and the demand for heavier material and for certain shapes increased, mills designed to meet a given demand or to roll a certain kind of product began to appear. Then it was that the smaller or older mills, which continued to roll a variety of sections and often stocked material that was retailed out later, were designated as merchant mills, in order to distinguish them from the specialty mills and those whose product was handled in large lots. Later on, especially in this country, the mill manner of handling materials and doing business underwent a change, and the mills were more or less divorced from the store house, so that these mills, while they continue to roll a variety of sections, always roll to orders. Thus, though they have lost all the characteristics, they still retain the name of merchant mills. Therefore, in this country a merchant mill is any small mill, say twenty-two inches and under, which regularly produces more than one shape.

Kinds of Merchant Mills: In touring the various works, the visitor is surprised and often not a little confused by the great number of and seemingly meaningless terms applied to these mills. Thus, there is heard the term "bar mill" applied to two mills of altogether different types. The term "guide mill" is apparently used in the same way. Added to these are such names as "Morgan mill," loop mill, shape mill, continuous mill, and semi-continuous mill, hoop mill, Belgian mill, combination mill, etc., and such local terms as the "iron mill," and the "steel mill," the "electric mill," or just "merchant mill," as at some plants where there is but one merchant mill. While one not familiar with the mills is inclined to think most of these names are accidental localisms, many of them are really descriptive of the mills and also form links in a systematic classification based mainly on construction and design. These terms and the classification of the mills is best explained from a historical viewpoint. For this reason it is desirable to trace very briefly the evolution of the small mill.

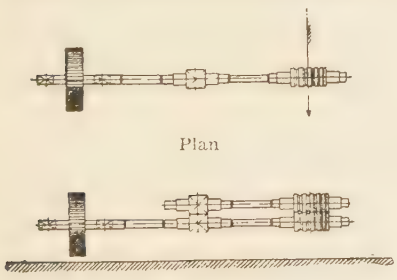


FIG. 172. First Merchant Rolling Mill.

Development of Merchant Mills: The first mill, which also stands for the simplest kind of mill, consisted of a single stand of rolls driven in one direction only, and for many years all bars or sections were rolled on this simple mill. No guides were used at first, and the roller guided and supported the bar between the rolls by means of tongs. In order to avoid the labor of pulling the bar around the mill, the catcher returned it by laying one end on the top roll, which carried the piece forward with little effort on the catcher's part. To avoid this idle pass, the idea of placing a third roll above the second, so as to work the bar as it passed in both directions, was conceived and resulted in a great economy in labor. Up to this point the bars were comparatively short, sixteen to twenty feet being the usual lengths. It was next discovered that a great saving in both labor and material could be effected by making the bars longer, but to accomplish this increase, a larger billet had to be used. The increase in the size of the billet was secured by increasing its length, which required wide heating furnaces, and by increasing the size of its cross section, which called for a greater number of passes for reducing than could be placed in one stand. To supply these extra passes, additional roll stands were needed. These stands were coupled together to form the roll train of Figure 173.

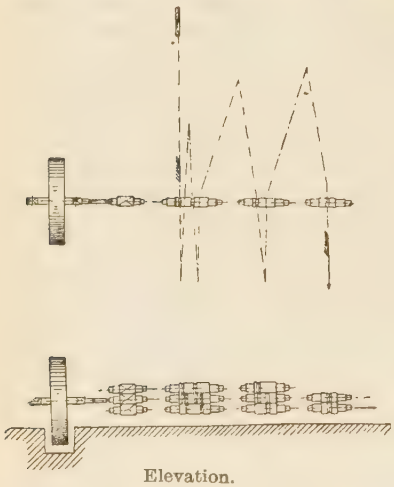


FIG. 173. Diagram of a Simple Type of Three-High Merchant Mill.

The Guide Mill: The rolling of rounds, which have always been an important product, led to the first use of guides. The method first used was like the method for hand rounds previously referred to, but a greater number of passes were used to finish the piece. Since the tonnage, especially on small rounds, was held down by the time consumed in passing the piece back and forth through the finishing groove, it was natural that the mill man should seek some way of reducing the number of these passes. This endeavor led to a really great discovery, namely, that a round could be rolled in one pass from an oval, provided the oval was of the right dimensions and was supported by metal guides. This success of the guide led to its use for other shapes, also, and to its adoption in modified forms to nearly all mills. Thus, another word, guide, came to be rather loosely used. In general, a guide is any device used to support the piece in the correct position during its passage through the groove. In order to perform this

function, the guide must fit neatly against the roll or rolls, so one end must be shaped to conform to the shape of the space in front of the rolls. Entering guides are usually of the closed type. They are made in two parts.

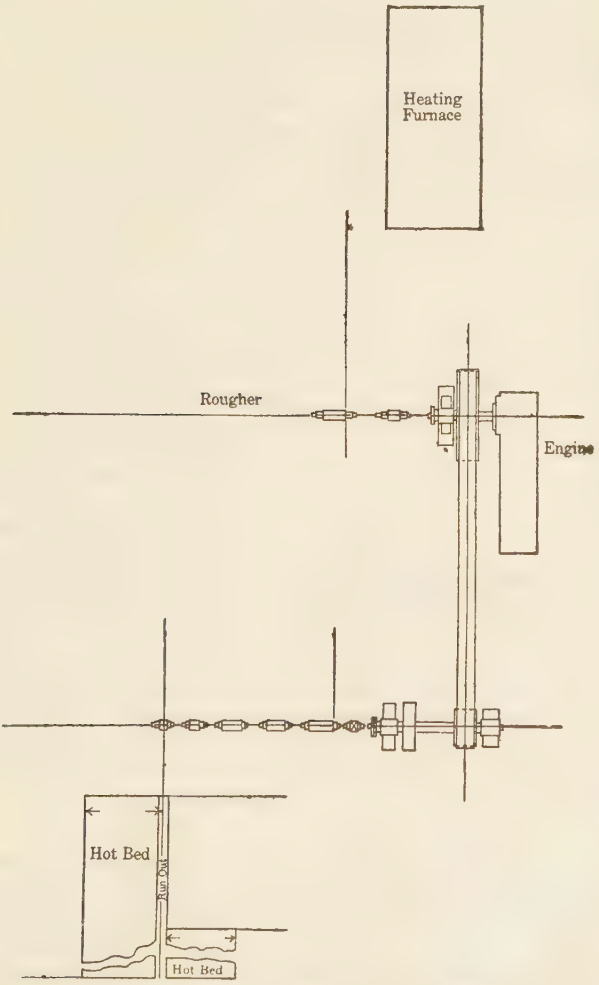


Fig. 174. General Layout for an Eight-Inch Guide Mill—Belgian Type.

In each of these two parts a groove is cut parallel to its long axis, so that when the two parts are fitted together the opening formed by the grooves

will be of the required shape of section to support the piece properly. The guide proved to be of immense advantage in another way, in as much as it permitted the rolling of very long lengths. Today, any mill designed to roll sections that require the use of guides may be called a guide mill.

The Belgian and Looping Mills: Though it was now possible to roll in long lengths, a serious drawback was encountered in the old and slow-going mill, for, if the piece were long and, especially, if the section were small, the steel would get too cold to roll before the piece could be finished. The remedy, of course, was found in greater speed, but here trouble was again encountered because of the roughing rolls which refuse to bite the billet if the speed is too great. Then there originated in Belgium the scheme of setting up an independent roughing stand that could be driven from the main drive shaft of the engine at a lower speed than the finishing train, which was driven by power transmitted by belt from a large pulley on the drive shaft to a much smaller one mounted on a short shaft connected with the train pinion. Up to this time the piece was rolled throughout its length in a given pass before it was started into the next. Who the man was, or what his degree, that was responsible for the next advance in rolling, history does not say, but doubtless it was some bold Belgian catcher who first conceived the idea of catching the first end as it came through the rolls and returning it immediately through the next pass, thus rolling the section in two passes at once. Since the speed of the piece on the delivery side is greater than that of the rolls, due to the elongation, the material overfed and formed a loop. By this looping scheme, the capacity of the finishing train was increased beyond that of the roughing stand.

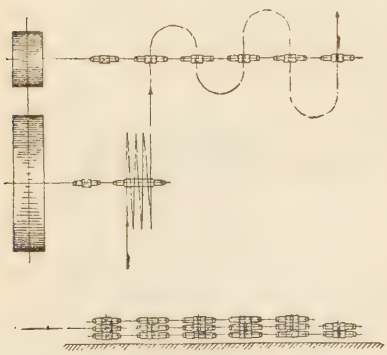


FIG. 175. Early Type of Looping Mill.

The Semi-continuous or Combination Mill: Such was the extent of the development until a few years prior to 1900, when two things combined to force another advance in the merchant mill; one was the previous development and success of the continuous mill as a semi-finishing mill; the other was the necessity for economy due to labor troubles and a severe depression in the steel business. So, in order to decrease labor costs and speed up the mill to the limit of the finishing train, the continuous rougher was installed to replace the single three-high roughing stand of the Belgian mill. By this inovation the mill force was decreased by about nine men, while the output was increased 50 per cent. The mill proper was then in a

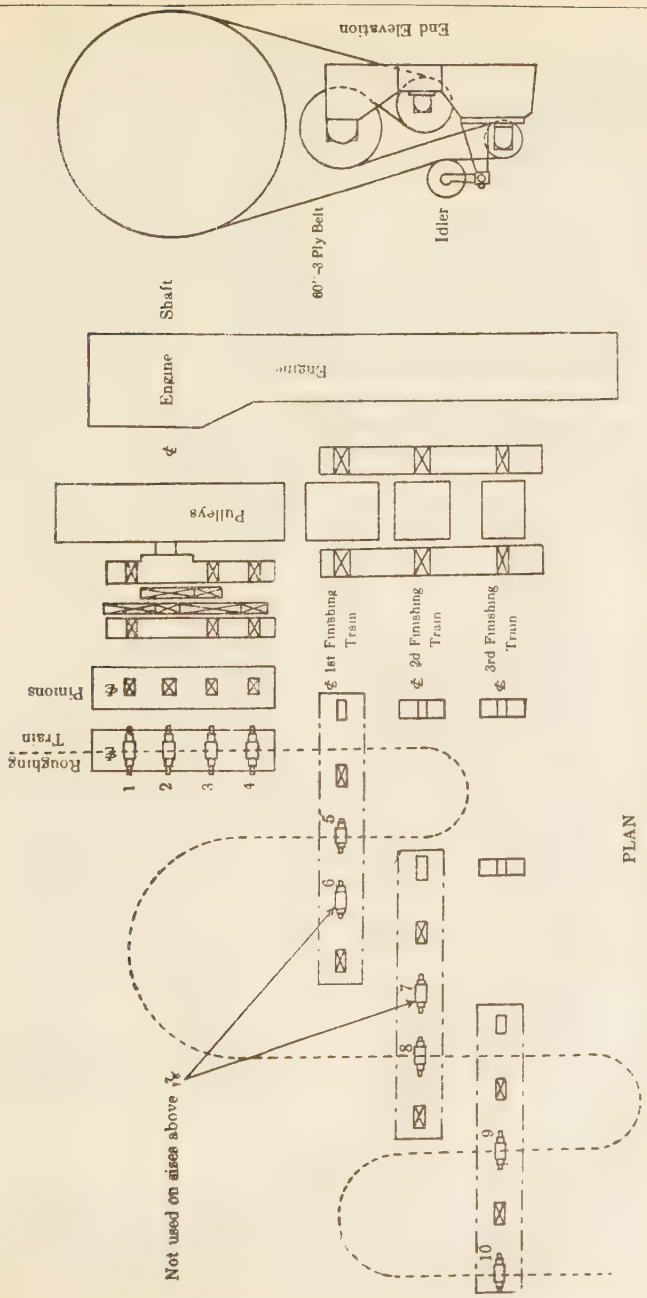


FIG. 176. General Layout for a Ten-Inch Mill—Later Type of Looping Mill with Continuous Roughing Stands.

position to roll in unlimited lengths and thus effect another saving; but two things combined to limit the length of the piece rolled, namely, the difficulty of handling long pieces on the old style cooling bed and the problem of keeping the bar uniformly hot for finishing. The first problem was solved by the invention of the mechanical cooling bed. These beds consist of a runout, in which are live rolls, for delivering the piece; a device for stopping and transferring the material, which is delivered at speeds as high as fifty feet per second, and at intervals of only one or two seconds between pieces; a system of notched or fingered racks, by means of which the hot bars are moved away from the runout; and a receiving table, also containing live rolls, by means of which the bars are delivered to the shears. Examples of these tables will be found at all modern mills. The problem of uniform heat was then solved by speeding up the mill; by locating the roughing rolls near a continuous furnace, as was pointed out in discussing the rolling of hoops; and by arranging the drive of the mill so that the peripheral speed of the rolls is increased in the successive passes to take up the slack in the loops. Another device, by which the number of hands employed about the mill was reduced, is the mechanical repeater. Many mills equipped with these repeaters are entirely automatic in operation of the rolls, and can roll material that is much too stiff to be turned or looped by hand.

The Cross Country Mill: While these improvements were being made in the looping mill, a mill of a different type altogether has been developed. It is known as the cross-country mill, and is intended for rolling material that does not lend itself well, on account of size or shape, to loop mill rolling. These mills involve the continuous idea, but the stands are placed so far apart that the piece must leave one set of rolls before entering the next. For carrying the piece from stand to stand stationary roll tables are employed. To save space and avoid complicating the drive the stands may be arranged on two or more parallel lines, and the direction of travel of the piece will be reversed during the rolling. Three-high stands are placed at the reversing points, so that, by means of mechanical repeaters and diagonally placed tables, the feeding of the mill is made automatic throughout. In the latest types of these mills, as for example the No. 7 mill at Duquesne, which made its first trial rolling in July, 1917, the three-high stands have been eliminated and two-high substituted, the piece being moved over from the first roll line to the second then to the third by transfer and skid tables. In general, the tendency is to return to the two-high stand, because it is the simplest as well as the strongest and most rigid in construction.

Future Development: From the preceding sketch, it would appear that the merchant mill, so far as the mill is concerned, has been developed almost to the highest stage of perfection. At present, the trend of improvement is in two directions, one looking toward economy in power and the

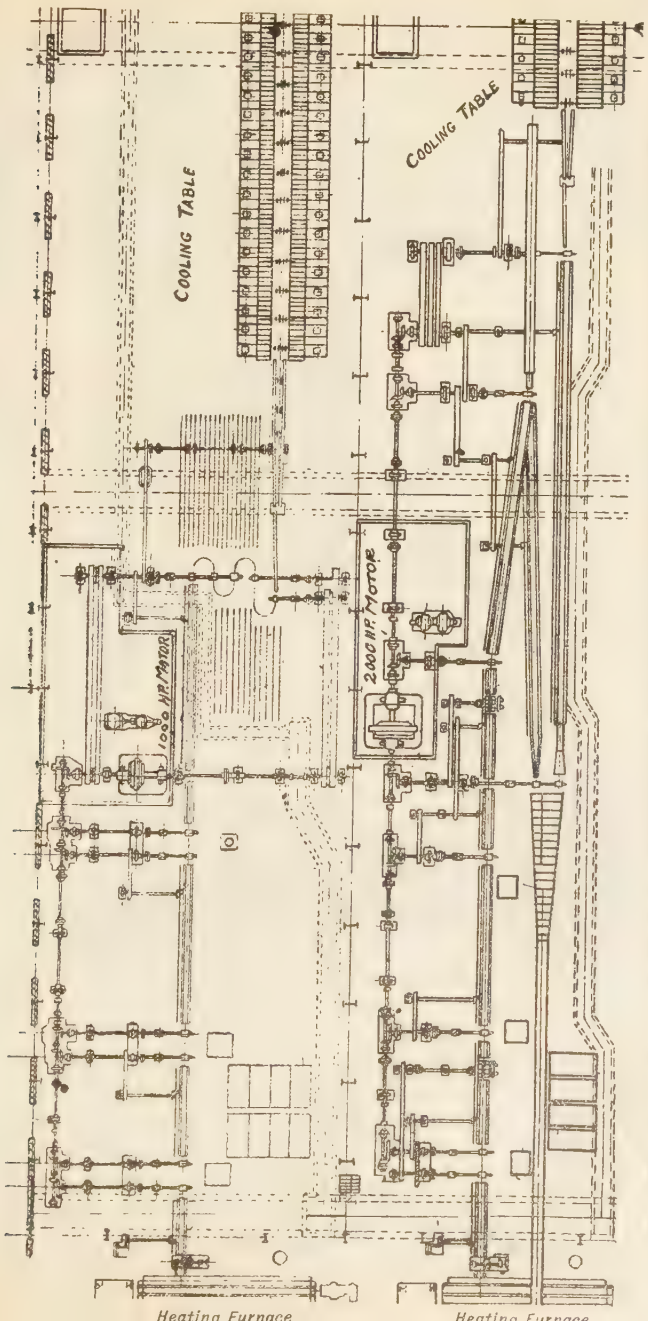


FIG. 177. General Layout for Eight-Inch (top) and Ten-Inch (bottom) Electrically Driven Merchant Mills. Examples of the more Recent Types showing part only of each Cooling Bed and Heating Furnace.

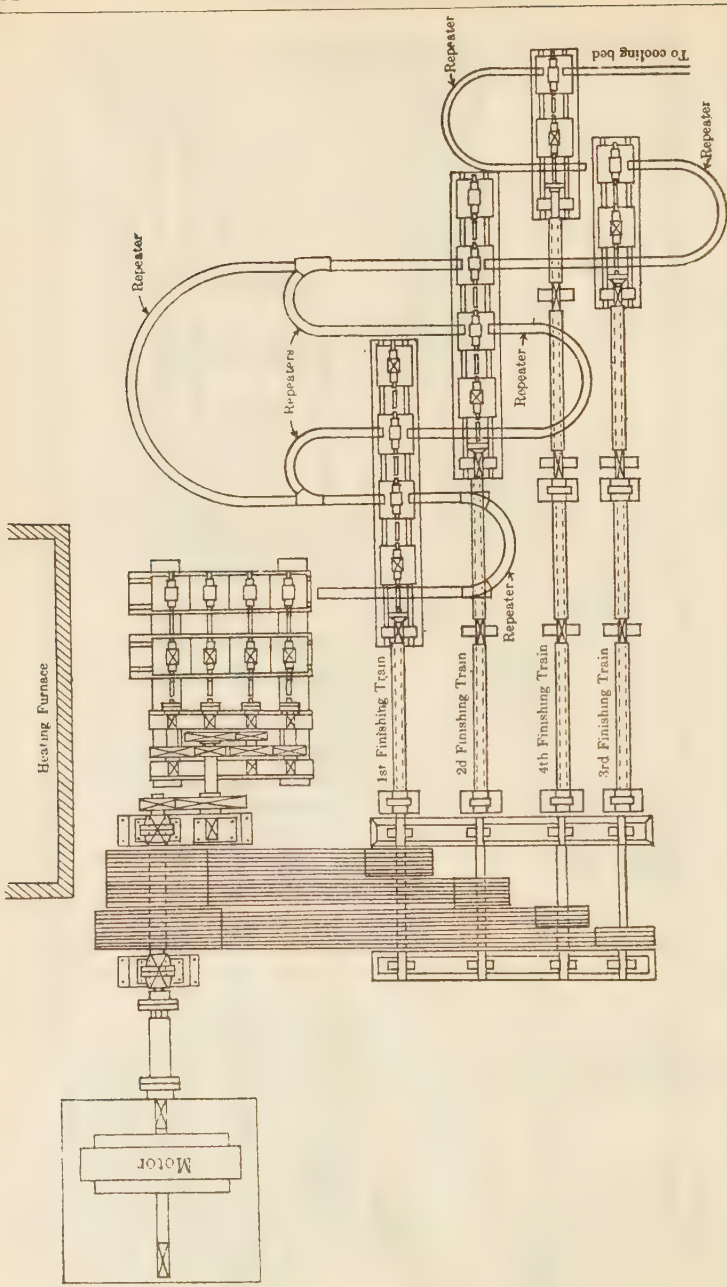


FIG. 178. General Arrangement Ten-Inch Merchant Mill, Electrically Driven Looping Mill with Continuous Rougher and Mechanical Repeaters.

other toward specialization. As to the first, the adoption of electricity for driving the mills has effected great economies. Much advancement has been made since 1900 in the construction of electrical motors, which, through supplemental equipment such as rotating resistors, balancing sets, etc., have reached a very high state of efficiency, and a great majority of the mills installed since 1916 are equipped with these motors. Specialization is taking two courses. Thus, more and more specialty mills are being erected, and other mills are being supplied with special equipment, such as supplementary roll stands, which adapts them to the rolling of certain sections yet leaves them free to roll other products, also.

SECTION III.

DESIGNING ROLLS AND MAKING UP SCHEDULES FOR MERCHANT MILLS.

Roll Designing for Merchant Mills: It does not require much imagination to see that the problems of the roll designer for merchant mills are many and the most difficult to solve. That the art of designing rolls for these small mills must have made wonderful progress is indicated by the recent appearance of sections of the most intricate design, yet rolled with minute accuracy. But the designing of passes for the sections is but one of the problems confronting the roll designer, as a visit to the mills will show. Among these should be mentioned the great number of designs, which require the most systematic filing and recording of rolls, templets, and tools. The ingenuity of the roll designer is taxed to the utmost to keep the number of rolls at a minimum. So, the visitor in the mills will find that numerous sizes, differing by only a few thousandths of an inch, are placed in the same roll. The efforts of the roll designer along this line are especially noticeable in the roughing stands. Here the process is merely one of reduction, the piece leaving the roughers in the form of a square or rectangle. To bring about this reduction one of five methods, or combination of passes, may be employed. Thus, in continuous roughing, the student will observe four methods in use, which may be designated as: 1. Diamond—square; 2. Oval—square; 3. Flat-and-edging; 4. All-diamond-to-square. In three-high roughers, either the flat-and-edging or the diamond-pass method is used. The following sketch is intended to illustrate these methods. Nearly all the shaping, except in the case of deformed bars already alluded to, is done in the stands, called the strands, immediately following the rougher. The strands are sometimes preceded by an auxiliary set of roughers called the pony roughers. The planisher may be employed as a last forming pass only or, in addition, to give a finish to the bar. The finishing pass is reserved exclusively for removing the little irregularities of the previous rolling.

Economic Features of Roll Designing: It scarcely needs to be pointed out that, aside from the successful rolling of the various sections, the chief incentive behind the efforts of the merchant mill roll designer

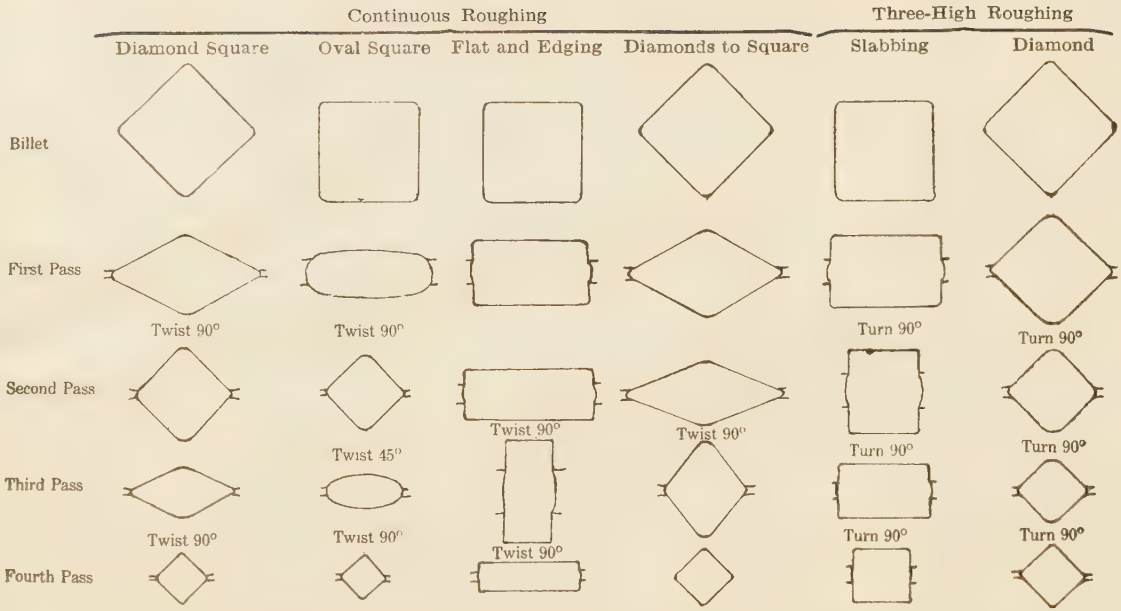
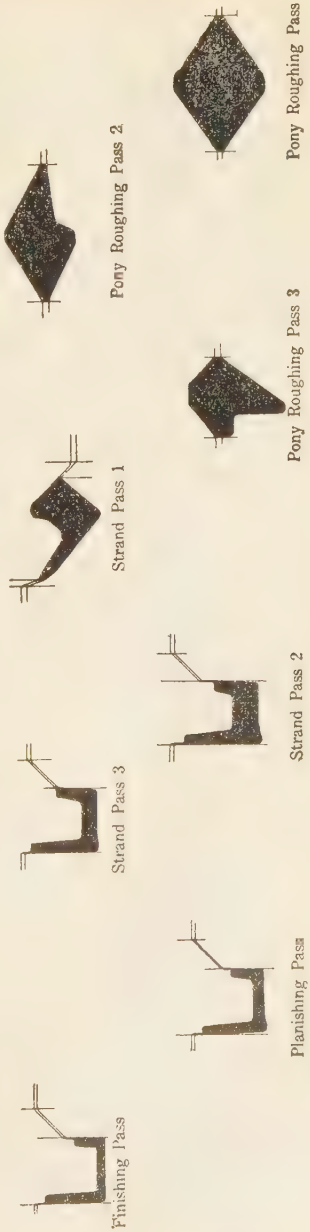


Fig. 179. Methods of Reduction Used for Roughing Rolls in Merchant Mills.

is found in the necessity for economy. The rolls, alone, as may be surmised from what has been said concerning their manufacture, etc., are very expensive, and a large number of rolls on hand means a large investment in something that is idle most of the time. Added to this feature is the expense of roll changes, during the time for which the entire mill is closed down. In the elimination of roll changes much depends on the way the orders are scheduled. This point should, therefore, always be considered in making up the mill schedules, and is a problem to be solved in making up promises of delivery for small lots. As an example of how scheduling is done, the system employed at the Upper and Lower Union Mills at Youngstown is explained.

Making Up Schedules—The Order in the Office: Upon receipt of the large buyers' schedule, which usually comes about the middle of the month for the following month, the respective schedule clerks pick out from the files the index cards corresponding to the buyers' schedule and file them in a desk file. At the same time all those index cards with promises on them for the next month are taken out and put along with those already in the desk file. In addition to these the oldest index cards are also worked in whenever it is possible. Before these index cards are put in the desk file, however, they are checked against the book orders for mistakes, etc., and the date of order. By this means it is known that the item is either in the desk file or out on the mill. The index cards in the desk files thus represent all the promised and scheduled material for the next month. From these files the schedule clerks make up rollings for their respective mills. For this



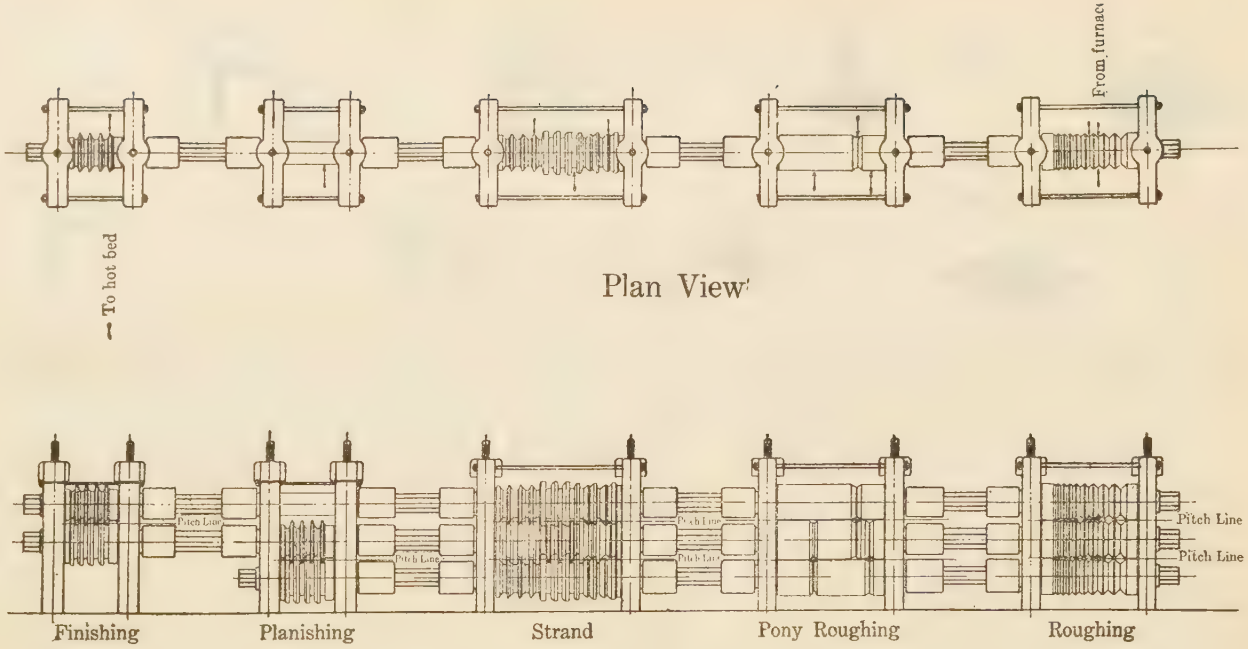


Fig. 180. Sketch Showing Passes and Location of Same in Rolls for Window Sash Section.

purpose index cards showing the different sizes of sections and grades of steel on the schedule are also kept. To keep the scrap loss on the mill to a minimum, the longest exact cuts are put first, the exact short lengths come next and after these are placed the common lengths. Therefore, when shearing the long exact cuts, the short ends may be sheared into the shorter lengths; and if a long piece comes at the end, it may be sheared to one of the long common length cuts. The amount of tonnage to a rolling varies with the mill and the section being rolled. In making up a rolling it must be watched that a car load of material is checked out, so material will not have to be piled. If there is not enough material at either Upper or Lower Mills to make up a car load for the customer the products for both Upper and Lower for that customer are combined to make up a car load, the shipping offices having previously decided at which plant to start the car. Sometimes an order will be transferred from one mill to the other so as to prevent this condition. In this case, the order is transferred by making out two correction slips. One of the slips goes to the one mill telling its foreman to cancel the order that is to be transferred, and the other goes to the other mill telling its foreman to reinstate the order mentioned. The correction slips are made out in triplicate form, a copy of each remaining at the order department, and the original and a copy of each going to the proper shipping office where the original is returned and noted to the order department, while the copy is kept on file at the shipping office. The schedule clerk in the order department keeps a record of the orders he sends to the mill order clerk for each mill and from time to time checks up with him regarding the amount of steel on hand. After a rolling has been made up, the index cards are hectographed and three copies are made. These copies are known as mill order sheets.

The Order at the Mill—Size of Billet or Bloom: The original index cards, together with the copies, are sent to the mill order clerk, who gives the index cards to the shipping office, keeps one copy of the mill order, and sends the other two to the mill foreman. These should be sent over to the mills at least twelve hours before they are to be put out on the mill, so that the foreman will have time to figure out the weight billet required and to order the steel from the mill stocker. Due to various influences, however, the orders are often sent out only a few minutes before they are put on the mill. In figuring out the billet or bloom required for the order, the foreman figures the length to which he can run the material on the cooling bed and obtain multiple lengths of the cut ordered, taking into consideration both the length of the hot bed and the mill practice. He then multiplies the mill length that the bar is to be rolled on by the weight per foot of the section, which gives him the weight billet or bloom needed, not allowing for scrap or furnace loss. About 10 per cent. is added to most orders to offset furnace and scrap loss. However, this factor changes with the section and the cut. Common length cuts on large material requires sometimes as little as 5 per cent., but on the other hand light material, such

as crescents, on which the cut is exact and the inspection rigid, the amount added will sometimes be as high as 25 per cent. In figuring the weight billet required, the width of the furnace must also be taken into account. Blooms for common grades of steel are furnished by the Ohio Works in different weights, increasing by fives from one hundred to three hundred pounds, while billets, unless otherwise requisitioned, are furnished in lengths of thirty feet. After figuring the orders, the mill foreman makes out a steel order with two carbon copies. The original is kept on file; one of the copies is given to the stocker, who sees that the billets or blooms are cut to weight and delivered to the heating furnaces; and the other is given to the steel yard foreman, so he can check the same against his records. The orders are then given to the shear foreman and the roller, the size of the section being marked on the margin of the latter's sheet in large clear figures in order to eliminate any possible error in size. When the shipping office receives the index card from the mill order clerk, the card is blue-penciled showing date the order was received from the order department. It is then returned to the mill order clerk who files it until he places the order on the mill. The card is again given to the shipping office when the order is placed on the mill, and, this time, the date the order is put on the mill is marked with black pencil. A shipping clerk looks up the book order and marks the index card with the information as to whether the material is to be piled or loaded into a railroad car, which is dependent upon how much material for that customer is being rolled. The marked index card is then filed according to size and section.

SECTION IV.

ROLLING PRACTICE IN MERCHANT MILLS.

The Roller: While the roll designer is indispensable, and the roll shop represents the heart of the rolling mill plant, much depends on the roller. He must be a man with not a little ability, capable of exercising good judgment at all times and possessing considerable practical knowledge. With closer and closer rolling tolerances being demanded by the customer and larger tonnages required, due to the rapid growth of the steel industry, the roller has been placed in the difficult position of meeting rigid specifications and breaking tonnage records at the same time. This achievement appears the more remarkable when it is recalled that all the training the roller gets is along practical lines. His only school is the school of experience in which a man is never graduated. It is manifestly impossible, therefore, to explain satisfactorily the knowledge of the roller or the method of his working. The best that can be done is to point out some of the duties of the roller and mention a few of the precautions he must observe.

Precautions in Rolling: In a word, it is the duty of the roller to see that the rolling is properly done and the material meets the specification

as to size, shape and freedom from rolling defects. In setting the rolls in the housings, care should be taken by the roller that they are plumb, square and level. If the rolls are not plumb, i. e., if the line joining their centers is not straight and perpendicular to a horizontal, the bar will not deliver properly, and trouble with the guides will undoubtedly occur. This condition is often caused by bearings wearing out or poor babbitting originally and can only be remedied by changing bearings or, in some instances, by the use of side liners or wedges. Should the rolls be out of square, that is, if the center of the pass in the top roll is not directly above the center of the pass in the lower roll, the bar will be out of square and will twist as it issues from the rolls. In order to square up the rolls, set screws which work against the bearings are provided on the sides of the housings, and thus the rolls can be thrown either one way or the other as the case may demand. The directions for correcting this fault are, in the language of the mill, "Follow the twist," and the top roll is always thrown over in the direction that the bar is twisting. In the event that the rolls are not level, that is, perfectly parallel, more work will be done on one side than on the other, with the result that the bar will not deliver straight but will tend to curve around toward the side on which there is the lightest draft, due to the other side being elongated the more. This condition may be remedied either by the use of liners or by operating the screw down at the proper side. Guides and guards play a most important part in rolling mill practice, and the proper setting of these is one of the roller's most important duties. His assistants may set the guides for the strand and planishing rolls, but those for the finishing pass are always set by the roller. Entering guides on the finishing passes are usually closed, the inner end being so shaped that it will provide sufficient bearing to hold the piece up in correct position while entering the pass. If the guides are not set properly, the bar will not be formed rightly. Especially when rolling rounds, the entering guides should be tight in order to hold the oval in a vertical position, for a leaning to either one side or the other will produce a high and a low shoulder on the finished round. The position of the guides on the delivery side is also most important, for since the bar has a tendency to follow the smaller roll diameter, the guide against which the bar is thrown must be watched most carefully. If the bottom roll is the smaller, then the bottom guide should not be placed too low, for the bar coming out would have a tendency to follow the roll down for a short space before striking the guide. This would cause an up and down kink, or a buckle. A short guide has the same effect.

Rolling Defects: In addition to working for the proper size and finish on the bar, the roller must watch for such surface defects as overfills or pinches, underfills, buckles, slivers, seams, laps, firecracks, roll marks, etc. Overfills or pinches must be watched especially in changing from Bessemer to open hearth steel, as the latter has more of a tendency to spread than does the former. When overfills occur, the amount of stock entering the pass

that is producing the overfill must be reduced by adjusting the rolls in preceding passes. Underfills are corrected by reversing these operations. Buckles are sometimes caused by worn out pinions. Slivers can be produced from many causes at the blooming mill or by the bar shearing against a guide or collar of a roll at the finishing mills. The former condition cannot be corrected by the merchant mill roller, but the latter can be eliminated by a proper adjustment of the proper guide or by reducing the stock in the bar which is shearing against the collar. Seams are defects in the steel that cannot always be corrected by the finishing mill, as they are usually formed in the bloom or the billet. A lap is caused by an overfill or fin being formed and then being doubled over and rolled down in the subsequent passes. This defect can be controlled by the roller by going back to the stand at which the overfill was formed and reducing the stock. Firecracks are caused by the rolls becoming overheated and cracking on the surface. These cracks cause corresponding small elevations on the surface of the bar, which in some instances condemn the material. When this defect appears, the roller "moves over" and uses a "clean" pass. The same procedure is followed when any other roll mark appears on the finished bar. Roll marks occur at equal intervals along the bar and signify that there is a piece out of the roll or that the roll is marking the bar with each revolution in some other manner.

Two Different Finishes on bars are furnished at the Youngstown plant, namely, common and special. The special finish has a smooth, highly polished appearance and is produced by cleaning all scale from the bar at the planishing stand and finishing at such a low temperature that no more scale will form on the surface.

The Special Finish is produced on rounds by holding the square back before entering the planishing, until a dark scale has formed and then bending the bar with a pair of special tongs as it enters the rolls. A stream of water plays directly upon the bar as it enters both the planishing and finishing passes, and scouring blocks covered with emery powder are used on the finishing stand in order to keep the pass clean. Material requiring the special finish is always rolled ahead of the common orders of like sizes, so that a clean pass will be available. Flats are not scraped in order to furnish the special finish, but are simply held back until their temperature reaches the critical range before entering the planishing pass. On large flats, water is used on the bar as it issues from the planishing, so that the scale thus broken up will be removed and not be rolled into the steel. Another reason for using water on large sections is that they will be delivered to the hot beds below the scale forming temperatures. Cooling is unnecessary, however, on small sections, such as crescents, half ovals and ovals, as these lose their heat so rapidly that even water is not used directly on the bar. A scraper, located at the entering side of the finishing stand,

is the only means used for producing the special finish upon these sections. Due to the fact that scale adheres more tenaciously to open hearth than it does to Bessemer steel, the latter takes a much better finish than the former. Open hearth steel will become smooth but does not have the highly polished appearance of Bessemer steel. It is the rollers' experience that Bessemer screw steel takes the best finish of any grade turned out at the converting mills. This grade not only takes a smooth finish but some times gives a mirror-like surface. It should be observed that the holding back of the bar to produce this finish may so retard the rolling as to decrease seriously the total output of the mill.

SECTION V.

SHEARING AND BUNDLING MERCHANT MILL PRODUCTS.

The Methods of Shearing and Bundling vary at the different plants according to equipment, product, location, etc., and no description of value yet general enough to be descriptive of all plants can be given. As the greatest variety of sections are produced at the Youngstown Upper and Lower Union Works, a brief outline of the methods and practices at this plant may be found of value.

Duties of the Shear Foreman: The man who is responsible for completing orders, i. e., for the shearing and the bundling on each mill, is the shear foreman. His force is usually composed of a shearman, a gauger, a push-up, a pull-up, and two or more bundlers. The first duty of the shear foreman is to keep the different orders, heats and turns separate on the cooling beds and to tag each item on the truck properly. The different lots are kept separate on the trucks by means of bands. A load sheet is made out for each truck, showing the material loaded on it. When the truck is full, it is the duty of the shear foreman to notify the yard master or dinkey engineer to pull the load to the warehouse, or shipping room. It is also the duty of the shear foreman to set the gauge for shearing the material, allowing a certain amount for contraction during the cooling process. The amount allowed on the smaller mills is one-fourth inch over or under for every five feet, but this amount varies with the size of the bar. When material is to be bundled, the weight of the bundles is nearly always specified, but when instructions are not given, it is the mill practice to bundle material to weigh 100 to 150 pounds per bundle. By multiplying the weight per foot of the section by the cut and dividing the product into the weight of a bundle, the shear foreman determines how many bars to put in a bundle; but in order to check himself up he weighs the first bundle

of each new cut. It is the object of the shear foreman to put the same number of bars in each bundle, as this not only makes all the bundles of uniform weight but facilitates the recounting of a bar order by the men in the warehouse. On some mills the head bundler counts the bars, while on other mills tally boys are employed. In bundling material up to twelve feet on domestic orders only two "Carnegie" bands are used. Up to twenty feet three "Carnegie" bands are used, while four are used on all cuts twenty feet and over.

Bundling Export Material: On export orders, the weight of a bundle is always specified, the weight usually being 112 pounds, so that twenty bundles make one gross ton. On lengths up to fourteen feet, three bands, marked "Carnegie, Made in U. S. A.," are used. From fourteen feet to twenty-two feet, four bands are used, and one additional is put on for every six feet above twenty-two feet. On all export orders, special "export" tongs are used, as with these tongs the material can be tied very securely. The following rules apply to the handling of export orders: All orders must be complete. All bundles, excepting the last, must contain the same number of bars. All bundles are to be tightly tied with "export" tongs whenever possible, and bands used are to be in accordance with instructions on orders. These instructions may call for export bands, plain bands, or wire. All export material must be loaded on separate trucks, except in very small orders, or when the material is needed by the warehouse to complete an order hurriedly. All trucks containing any export material must bear a red export tag, and all excesses are to be loaded on trucks but kept distinctly separate, tagged plainly as "Excess," and showing order number, customer, size, etc. The name of the man who is responsible for tallying and bundling is placed on the tag, and all orders are very plainly tagged, the tags being so placed that there is little liability of their being torn, pulled off or made illegible. On all trucks are placed load sheets which are put in oiled envelopes so that weather conditions can not destroy, or blur, the writing.

Special Bundling: Some material, such as ovals, tees, etc., often specify "Tie with wire," while other orders, especially for large material, specify the material to be shipped loose. A good many orders, such as hoops, flats, rounds, squares, and small nut steel, are often ordered coiled. This is accomplished by means of coilers with adjustable pins so that coils of different diameters can be furnished. The usual diameter, however, is twenty-four inches. These coilers are located at one end of the hot bed or at some other convenient point according to available space. All coilers are electrically driven.

Handling the Material in the Warehouse: When the truck load of material arrives at the warehouse, the pile-boy takes the load sheet into the office and gets the corresponding index cards, because the load sheet shows only the order number, size, cut, grade of steel and remarks. The index cards show customers name and loading and shipping instructions.

As each item is weighed off from the truck, it is entered on a weight sheet by a weigh-man and checked off on both the index card and load sheet. If the index card is marked "Car" a car is started for that customer, if this has not already been done, and material is so loaded. If index card is marked "Pile" the item is piled and so noted on the weight sheet. One weight sheet is made out for each truck load, and when this car has been weighed off, the sheet is checked off on the car card, of which there is one for each car, and returned to the office. Here the weight sheets are checked against the order books. Memorandums are made out for the items that have been piled so that these can be given out to the weighmen when a car load has been started for the customer. When an item of an order is under weight or short in number of pieces, the shortage is discovered by a weekly survey of the order books by a clerk in the shipping office, who makes out a reindex card for the shortage and notes the date made out with blue pencil on both the reindex card and the book order If, however, there is a chance to get the item on the mill immediately, the book order and the index card are black penciled. A rolling order is made out from the reindex card and hectographed, after which the index card and three mill order sheets are given to the mill order clerk. He returns the reindex card to the shipping offices, and if he does not have the grade of steel in stock, he has to make out a requisition for it, the procedure then being the same as for ordinary orders.

Straightening: At the lower mill, straightening is done by the Labor Department, machines for this purpose being located at three different places. These machines are of the seven roll type, the rolls being built up in a casting similar to roll housings. Four rolls are below and three above, the bar passing between in grooves which are designed to fit each separate section. On account of the vast amount of tire and window sash sections rolled at the Upper Mills, the straightening is under the jurisdiction of a special department for that purpose. Angles and sash sections, moulding tees, and mud guard sections are straightened at the mill, there being a straightening machine located at each mill where such material is rolled. Round edge tire, however, is straightened in the tire house, where two straightening machines of a new type are located. These are more flexible than the old type and are more easily adjusted to the various sizes.

Invoicing: After the cars have been loaded, the car cards are taken into the shipping office, and from these, invoices are made out. The original office copy of the invoice, which is made out in the shipping office, is sent to the order department where it is carefully checked against the book order, the number of bars or bundles and tonnage being entered on same. The invoices are next given to a clerk who enters all detailed information on a "recap" sheet. The credits for the various sections and sizes are also entered under the proper headings on a "credit recap sheet."

SECTION VI.

INSPECTION DEPARTMENT OF A MERCHANT MILL PLANT.

The Inspection Department makes all physical tests and keeps records and samples of the various sections. One of the duties of this department is to inspect and accept or reject all special steel before being rolled into finished product. Check analysis is made of all steel requiring the same, and a close inspection of all material when being rolled is provided for. All special steel ordered from the semi-finishing mills must pass inspection by this department. Approval or disapproval of material is based upon chemical analysis and surface conditions. Only very low limits for the various impurities are allowed on special steels, and the inspection is very rigid. Consequently, any heats not falling within the requirements must receive special attention. Much in the way of good judgment is required to dispose of such heats satisfactorily. Usually, the department will endeavor to consult the customer before permitting an off grade heat to be rolled as originally planned. Certain orders require the ladle analysis to be checked before being rolled into the finished bar. Orders requesting check analysis are held in the yard until drillings from the billets are analyzed. If this analysis shows that the composition of the steel is as ordered, the steel is rolled on the order for which it was originally intended. If the check analysis does not practically agree with the ladle analysis, the steel is applied on a less particular order. Check analysis may also be made on finished material. Some orders require that the steel be inspected for surface defects before rolling. In such cases each billet is carefully examined to detect any slivers, seams, checks, or faulty shearing that may occur. Billets found to be defective are chipped and put into condition for rolling if at all possible. When orders specify physical requirements, it is then the duty of this department to supply such chemical specifications as will fulfill the physical requirements.

Another Function of this Department is that of mill inspection, which is one of most importance. In this capacity the department acts as a check upon the rolling. Mill inspection requires one man on each mill, devoting his entire time to gauging and watching for faulty steel. Sections not fulfilling the prescribed measurements are either held for further inspection or thrown out as scrap. The rollers as well as the inspectors, have the given dimensions and tolerances. The inspectors check the rollers and inform them of any faults that the rollers themselves have not already detected. In case an inspector does not accept steel as rolled, and the roller continues to make the section, the inspector signals for the department superintendent and lays the case before him. If the fault cannot be remedied, and it is known the customer will not accept the steel as rolled, the mill must go off the order. The defects watched for most closely depend upon the section being rolled. Accurate size applies to all sections.

For the more complicated sections templets are furnished. Usually one exact and one full templet is made. For gauging rounds, squares, flats, etc., only a gauge and micrometer is used. Readings on the micrometer are accurate to .001 inch, while on the gauge one-sixty-fourth inch is about the most exact reading that can be determined. Other tools used for special purposes are squares and steel tapes. The square is used to detect diamonding in certain instances where each surface must be at right angles to the adjacent one. The tape is used when inspecting clip sections, to determine the regularity of the impressions that are rolled on the bar.

Surface Defects: The inspector is responsible for the detection of surface defects. These may appear as buckles, kinks, overfills, underfills, slivers, laps, seams, or burned steel. While the nature and causes of these defects have already been more or less fully explained, the following resumé of defects most likely to occur in merchant mill rolling is appended for ready reference:

Buckles and Kinks: A bar, when delivered from the finishing rolls, may be wavy, either up and down or sideways. The former is known as a buckle, while the latter is a kink. These defects are more injurious to some sections than others. However, all sections should be rolled as free from buckles and kinks as possible. Crescents have a tendency to buckle, consequently they must be watched closely.

Fins: If a bar has a fin or extra amount of metal at the sides where the finishing rolls come together, the bar is said to be overfilled. Bars rolled for cold drawing must be free from overfills, for these draw into laps. On the other hand, in order to get perfect corners on half ovals, a well known file manufacturer requests a small overfill at the edges.

Underfills: When a bar is scant in certain dimensions or when it is not completely filled out, the bar is said to be underfilled. This defect sometimes appears on rounds and channels.

Slivers are loose pieces of steel rolled flat on a bar. They may be present on the billet or be caused by faulty shearing, or incorrect entering of the bar in a closed pass. Slivered steel is thrown out as scrap and seldom held for further inspection.

Laps: If a bar is given a pass in the rolls after an overfill has been produced, a lap usually results. This defect is especially liable to occur with skelp, hoop and cotton-tie. Faulty ingots and poor rolling at the semi-finishing mills also cause laps.

Seams: Steel must be inspected carefully for seams, a surface defect always difficult to detect. A seam is a crevice in steel that is closed up but not welded. Seams are caused by blow holes and cracks in the ingot, as well as faulty methods of rolling. They render steel unfit for hardening.

Burned Steel shows up in the finished bar in the form of rough, checked edges. Burned steel is ruined, and the only alternative is to scrap it.

Roll Marks: Sometimes a roll is nicked, or a piece breaks off the roll, resulting in periodic impressions along the bar. The defect is corrected only by a new pass. Fire cracked rolls make similar impressions.

Finish: The finishing pass, if worn, does not give a smooth surface, consequently when the surface of a bar is not up to the standard in finish the pass must be changed. This defect is especially objectionable when rolling cotton tie, hoop, skelp and sections requiring the special finish.

Pipe: The inspector must watch the sheared ends of bars for piping. This defect, however, is usually detected at the billet shears before the steel is charged.

Testing for Defects: Tests for detecting some of these defects are employed by the inspectors. The tests most commonly employed for this purpose are the upset, forging and pickle tests. The upset test consists of heating a short sample piece in a forge or furnace and upsetting under a hammer. This is a severe test and readily shows up seams and laps. For forging tests, a bar about ten inches long is heated and forged along the longitudinal axis of the bar, which is then nicked and broken. Piped steel is readily detected by this treatment, as the forging opens up the pipe. The upset test is more often used than the forging test, especially when rolling forging steel. The pickle test consists of immersing for a few moments short pieces of the material in dilute sulphuric acid. The acid removes the scale from the bar, exposing to view and exaggating any surface defects that may be covered by the scale. Tests pieces of hoop and file steel are pickled. At the Youngstown Upper and Lower Union Mills all forging tests must be turned in for the personal inspection of the department superintendent, while the pickle tests are saved at the test house for six months before being discarded. With hoop, the pickled samples are held in a vise and the edges turned over with a hammer. This distortion of the metal opens up any laps that may be present. On special sections the inspectors are required to save samples every half hour. These are bundled together, properly tagged, and sent to the test house, where they are saved for three months.

Other Duties of Inspectors: Besides inspecting material for surface defects, the mill inspector must check the bundling requirements as well as the length of cut. This practice reduces bundling and shearing errors to a minimum. An hourly report with carbon copy is made by each mill inspector. This report shows the variations in size of the bar for each hour of the day. Notations are made of any steel held up and the cause of the same. These reports must be delivered to the inspection office at the end of each turn. Since the different sections are gauged differently, the make-up of the reports will differ accordingly.

Manner of Gauging Different Sections: Rounds are gauged on four diameters, distinguished at the mill as top-and-bottom, sides, and high and low shoulder. By top-and-bottom of a round is meant those two surfaces subject to compression in the finishing pass, and by sides is meant the points opposite the clearance between the rolls in this pass. The shoulders lie between these two diameters. The longer of the shoulder diameters is called the high shoulder, the shorter the low shoulder. Three samples are taken from each bar gauged, namely, front end, middle and last end. These samples are taken at the shears as the original bar is being cut into the lengths ordered. The top and bottom of a round may be distinguished from the sides by the way the scale is broken along the sides. If an overfill occurs, it shows also on the sides of the round. Usually, the ends of a mill length of a round are slightly overfilled. Flats, squares and nut steel are gauged for width, thickness and diamonding, but only the variations in width and thickness are reported. Cotton-tie, hoop, and skelp are reported for width and gauge thickness. Special sections are usually gauged by means of templets, but certain overall dimensions are generally given on the report. A sketch is sometimes made and the important dimensions lettered. The hourly variations for these dimensions are then inserted under the proper heading. Clip-iron, box-strap and bit-mouth are peculiar sections requiring special attention for gauging, and the various dimensions must be watched to get the section uniform. Inspectors at the cotton-tie mill have special duties to perform. They must get from each buckle machine every half hour a sample, which must be properly tagged and taken to the department superintendent for personal inspection. They are required to weigh ten bundles of cotton-tie every half hour and to post the weight on a blackboard in plain view of the roller. Concrete bar is rolled to weight, and inspectors must check the weights of the shear foreman. If for any reason an inspector is not willing to take the responsibility of passing slightly defective bars, the trucks loaded with such steel are marked with green tags, signifying, "hold for further inspection." This steel is examined by the assistant chief inspector, who either scraps the entire lot or details a specially instructed inspector to sort the good from the bad. Uses for which steel is rolled, as well as customers' claims, offer guides as to what defects a customer can accept.

CHAPTER X.

CIRCULAR SHAPES.

SECTION I.

SOME GENERAL FEATURES PERTAINING TO THE ROLLING OF CIRCULAR SHAPES.

The Rolling of Circular Shapes presents one of the most interesting studies of the rolling mill industry, because it is the latest development in rolling, and, though the idea of rolling wheels originated in Europe, it is in America that the art has been most highly developed. The beginning of this branch of the industry dates from the year 1903, when solid rolled steel car wheels were first used under freight cars. The use of such wheels resulted from the introduction in 1896 of all steel freight cars, which on account of their increased weight and great carrying capacity required a stronger and tougher wheel than any that had been made up to that time. It was to meet this requirement that Mr. Charles T. Schoen, who was the pioneer in the manufacture of all steel cars, perfected the mill, which now bears his name, for rolling these wheels. Later on, Mr. Schoen's method of preparing the steel, which will be explained later, was much improved by the Carnegie Steel Company, who purchased this mill in 1908. Considered from the standpoint of circular shapes in general, the Schoen mill has the one drawback of a very limited product. Being designed for one particular purpose, it can roll only car wheels, or wheels of that class, and of these it is limited to wheels between twenty-six and forty-two inches in diameter. For forming wheels less than twenty-six inches in diameter, the Carnegie Steel Company has found that the forging press gives the most satisfactory results.

Preparing the Blanks: The circular shapes all require a round blank to start with. Mr. Schoen originally sheared his blanks from slabs with a specially constructed punch-like shear, the further work being then completed in much the same manner as it is done today. But this method had the serious fault of producing a wheel in which the line of segregation, or pipe, if any were present in the slab, was located diametrically across the wheel and terminated at both ends in the tread. From what has already been said about pipes and segregated steel, it is easy to see how this location of the segregated area might develop defects at these two opposite points. As has already been intimated, the Carnegie Steel Company was responsible for bringing about the correction of this fault, which is removed by locating the segregated line at the center and at right angles to the radii of the wheel, where any faulty material may be punched out for the bore. It is

evident that the line of segregation may be so located in any one of three ways, namely, by casting the blanks individually, by cutting the blanks from round or hexagonal ingots, and by rolling the ingots into a round bloom from which the blanks may be sheared or sawed. All these methods are in use by the various manufacturers of wheels, but it would appear that the second and the third method should produce the best wheel, because more work is put on the steel. The third method is the one used by the Carnegie Steel Company. The round blooms for the Schoen mills are rolled at present (1925) on a twenty-eight-inch blooming mill at Homestead. Here a 22″ x 22″ ingot is slowly and carefully reduced in from twenty-one to thirty-one passes to a round bloom, eleven or fifteen inches in diameter for forged products, or fifteen inches in diameter for all wheels that are to be rolled at Schoen. From the blooming mill, the bloom is delivered to a patented shear, known as the Slick shear, which is so located, in conjunction with the delivery table and the manner of rolling, that first cuts are made from that part of the bloom corresponding to the bottom or butt of the ingot. This first cut, usually about 5 per cent. of the ingot, is just sufficient to square up the butt end of the bloom and is always discarded. The remainder of the bloom, excepting the discard for pipe, is then cut into lengths to give the proper weight of metal required in the wheel, with an allowance of ten pounds over or under weight, and, if requested, each cut is hand stamped with a letter to indicate its position in the ingot, starting with A for the first cut next to the discard at the top of the ingot. Cut A, and often cut B, also, is used in making wheels for the use of the Steel Corporation only. In any case the total discard, which may include both A and B cuts, on wheels to the customer is never less than 25 per cent., which amount is sufficient to insure sound steel in the wheels. For marking the heat number and weight of cut, the shear is provided with a stamp mounted on the revolving clamp for the shear knife, so that each disc, or blank, is plainly stamped with its heat number and weight. From the shears the blanks are taken to a shipping yard, where they are carefully inspected for surface defects, which are cut out by means of pneumatic chipping tools. Such of the blanks as pass this inspection are then sent to the mills to be worked into wheels.

SECTION II.

THE CARNEGIE SCHOEN METHOD FOR MANUFACTURING STEEL WHEELS.

The Carnegie Schoen Method: At the Schoen plant, which consists of three separate units, the finished wheel is produced in several stages, the number of which depend upon the kind of wheel, the unit in which it is made, and the working conditions of the heating furnaces. Upon receipt of the blanks at the plant, they are check weighed, and the heat number of each blank as well as the letter indicating its position in the ingot are

all recorded in the form of a serial number. The blanks are then charged in order into a reheating furnace, where they remain for about three and one-half hours. In the older units, mills number one and two, the reheating furnaces are all of the regenerative type and use producer gas; but in the most recent mill, or number three, the first furnace is of the continuous type, the bottom of which is inclined sufficiently to cause the blanks to roll down from the feeding end as rapidly as they are removed at the drawing end. This type of furnace heats the discs very slowly and gradually, because it is intended merely to give the discs a preliminary heating, and its temperature is therefore low. At the drawing end, the temperature is maintained at about 800° C. After being subjected to this preliminary heating, the discs are transferred to a regenerative furnace for the final heating previous to forging. When the discs have reached the proper temperature, they are withdrawn from the furnace and taken to the forging presses where each is forged to a shape resembling that of the finished wheel before dishing or coning. As to dimensions, this forged blank is from four to five inches under size in diameter, some three-fourths inch over size in that part of the web near the rim, somewhat oversize, also, in depth of rim, a little oversize in width of rim, but of correct or slightly full size in the hub and a small part of the web next to the hub.

Forging the Blanks—First Method: The forging may be done in one heat or two heats and on one press or on two different presses. When two heats are used, two presses are usually employed for the forging. In this method, the disc is cleaned of scale on its two ends and then placed vertically in the first press, where it is first perfectly centered by two arms which engage it from opposite sides of the press and so support it till the top die has descended upon it. In this press the bottom die corresponds to the outside face of the wheel, while the top die is plain, but may be slightly convex to cause a radial flow of the metal in taking the shape. The pressure, applied in successive steps by means of accumulators and intensifier, starts with about 700 pounds per square inch, then increases to 2500 pounds and, finally, to as much as 5000 pounds per square inch, if needed. At the beginning, the scale is cracked from the disc and falls into the bottom die, from which it is blown by means of a steam jet, in order to avoid pitting the surface of the blank. This pressing is, in itself, a severe test upon the metal, and any flaws, such as seams or cracks, are sure to be exposed, although they seldom occur. When such flaws do develop, the blank is scrapped at this press. The perfect blanks are now placed in a second reheating furnace, where their temperature is equalized and brought again to the forging point. When these conditions have been attained, the blank is cleaned of scale and placed in a second press, in which the top die conforms to the shape of the inside face of the wheel. Before applying the pressure, a little fine coal is thrown on the bottom die and upon the blank to prevent the dies sticking and to keep their surfaces smooth. After this forging, the blank is placed in a third press, where the bore is punched.

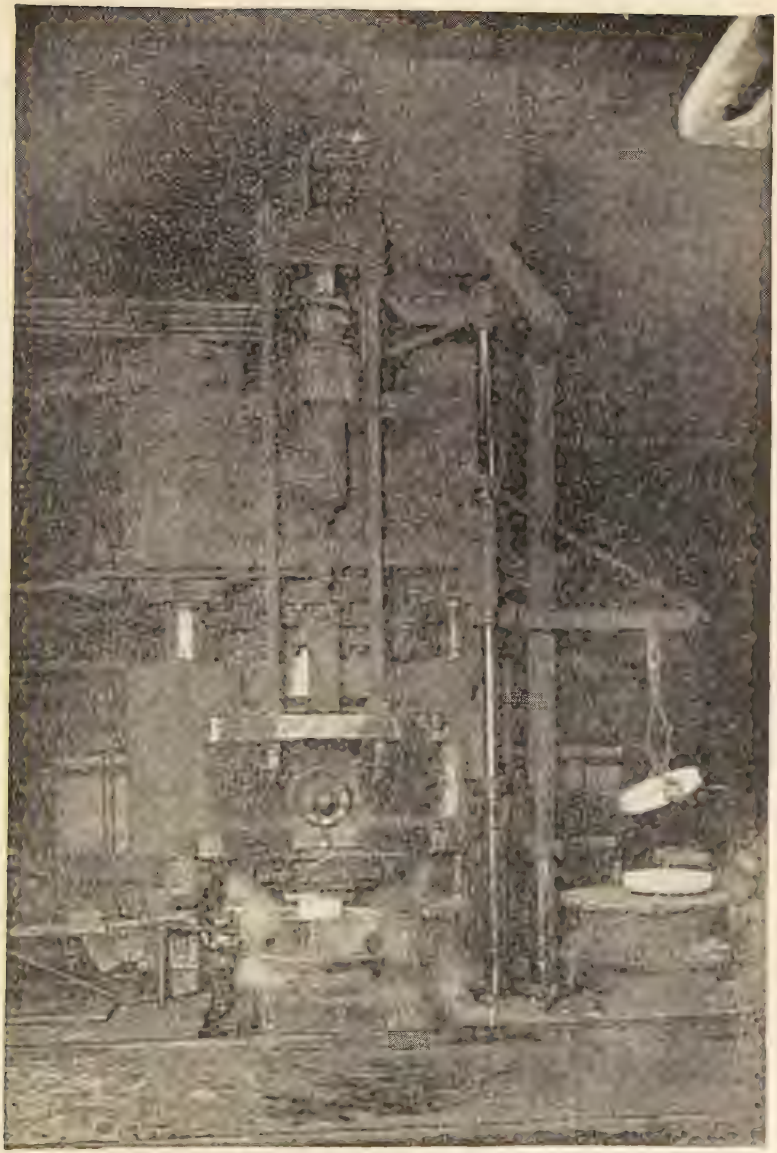


Fig. 181.—View of 7500-ton Hydraulic Press, Forging Wheel Blanks.

During the punching, the hub of the wheel is supported in neatly fitting dies in order to avoid forcing this part of the wheel out of shape.

In the Second Method of Forging, the press is provided with the two top dies mentioned in connection with the two presses used in the first method. These dies are mounted upon a sliding frame in such a manner that either may be brought at will beneath the piston of the press, thereby dispensing with the first forging press and permitting the forging to be accomplished in one operation when the conditions are favorable. Thus, if the blank is at a temperature sufficiently high and is evenly heated throughout, the second top die, conforming to the inside of the wheel, is brought over the blank, and the forging is completed in a single stage. If the conditions are such as are likely to cause an uneven flow of the metal, which results if the blanks are unevenly heated, the plain die is used first, then the inside die is moved into position and the pressure applied, thus forming the blank in two stages, but on a single heating. The bore is then immediately punched as in the first method. After the forging, by whichever method that may have been used, and the punching of the bore, the blank is placed in a reheating furnace where it remains until it has reached the proper temperature for rolling.

The Rolling Mill: The two older mills are very similar in every detail of their construction, but in the number three mill, which made its first trial rolling June 5th, 1917, a few changes looking toward an improvement in construction over the older mills have been made. For this reason this mill, rather than either of the older ones, will be described. This description is, however, made rather brief, for the mill, itself, is a somewhat complicated piece of machinery, as the reader will surmise when he is told that seven rolls play upon the wheel at one time during the rolling. These rolls consist of one tread roll, two web rolls, and four (2 sets) rim rolls, and are supported, together with all their bearings, pinions, or gears, adjusting screws, levers, etc., in one pair of horizontal housings, which are large steel castings placed one above the other. The bottom housing lies directly upon the mill foundation and forms the support for the rolls and for the top housing some four feet above it. The housings are held apart by suitable pillars or posts and are bound firmly together by means of immense bolts. Between these housings the rolls are located; they may be described as follows: The largest roll is the tread and flange roll. In form it resembles a wheel, some thirty-three inches in diameter, and is so located back near the central point of the housings that, during the rolling, it revolves in the same vertical plane as the wheel and bears upon its tread from the rear. Its face is somewhat wider than the rim of the wheel and is grooved to correspond to the tread and flange. It is friction driven and is carried on a slide bearing, so that, by means of a screw, which connects the sliding box to a fixture at the rear of the housings and is operated through a worm shaft and gear by means of a 15 h. p. electric motor located on

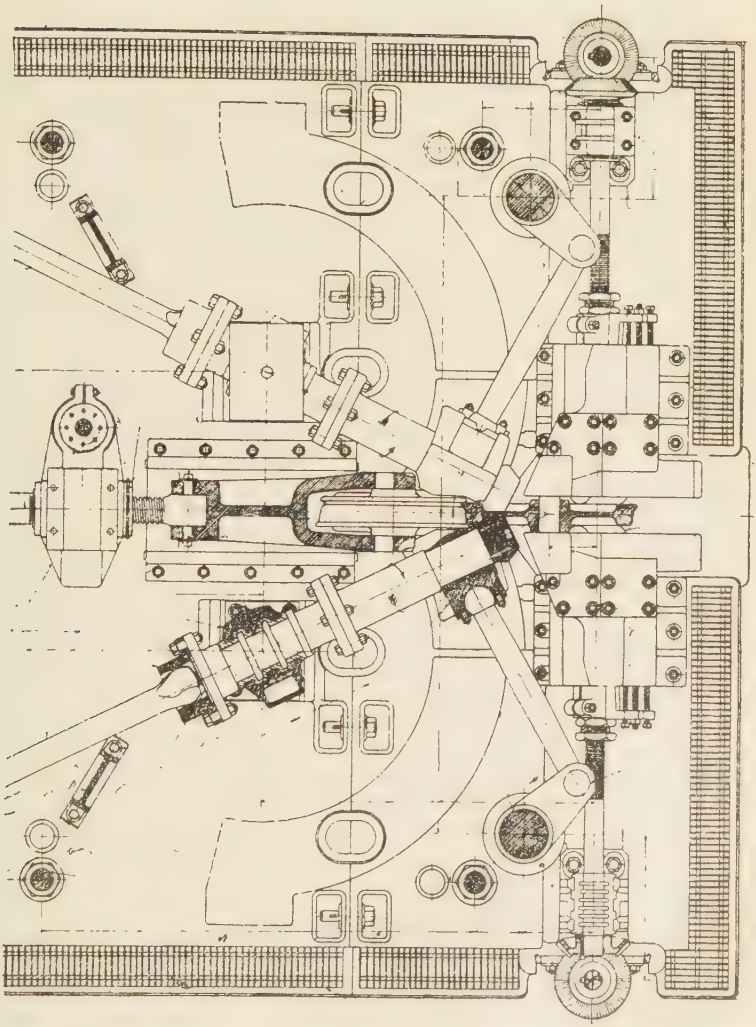


FIG. 182. Drawing of Schoen Mill Showing Wheel with Web, Tread, and One Set Rim Rolls in Position at End of the Rolling Operation.

top of the upper housing, this roll may be moved backward or forward at the will of the operator. Few operators, however, move this roll after the mill is once adjusted to roll the wheels of a given size and type. On the opposite sides of the tread roll are located the two web rolls. They are about three feet in length, lie in a horizontal position and extend inward, so that their center lines form angles of nearly 30° with the center line of the mill and intersect at a point near the center of the wheel that is being rolled. On their front ends they carry the rolling heads, or surfaces, which conform to the shape of the wheel beneath the rim, while their rear ends are anchored in rotating coupling boxes. Light steel spindles, some five feet in length and provided with proper wobblers, connect these couplings to the two bevel gears, one of which stands on each side of the mill at the rear. These gears mesh into similar gears mounted on the driving shaft of a 750 h. p. D. C. motor (500 volts, 1100 amperes, 130 r. p. m.), which, located at the rear and on the center line of the mill, is used to drive these rolls. Just back of the rolling heads, these rolls are supported in sliding bearings which permit of their being spread as desired. The pressure for rolling is transmitted to these bearings through radial levers, the long arms of which are each attached above the housings to the same screw, so that the same motion, but opposite in direction, and equal pressures are imparted to the two rolls at the same time. This screw, which corresponds to the adjusting screws on ordinary mills, is actuated by means of a 15 h. p. direct current motor (220 volts, 64 amperes, 550 r. p. m.). By this means, the power of the motor is multiplied many times and is capable, at its maximum, of exerting such pressure on the web rolls as to stall the mill. As to the relative altitude of these three rolls, they are so placed that their lines of contact with the wheel in rolling and the axis of the wheel, itself, all lie in the same horizontal plane. The four rim rolls, which are friction driven, are located, one pair above and one pair below, the web rolls, so that all the rolls lie within an arc of 180° of the circumference of the wheel being rolled. These rolls are approximately twelve inches in length and nine inches in diameter, and are so placed that the projected axes of rotation of the two on either side of the wheel intersect at the axis of rotation of the wheel. They are mounted upon sliding frames attached to the front of the mill housings. These four frames are moved by horizontal screws connected by vertical worm shafts and gears to a common shaft, which extends in front of and beneath the housings and is operated by an electric motor set some eight or ten feet to the right of the mill, measuring from the side of the housings. In this way the spread of these rolls is made uniform. However, the bottom set of rim rolls, due to the manner of rolling, do nearly all the work. An indicator, mounted on the upper horizontal screw attached to the sliding frame on the right side of the mill, is in plain view of the operator, who is able, by this means, to read the spread of the rolls and thus control the width of the rim. These rolls may be so formed that they will roll the sides of the rim at a slight angle to the vertical, so that these surfaces

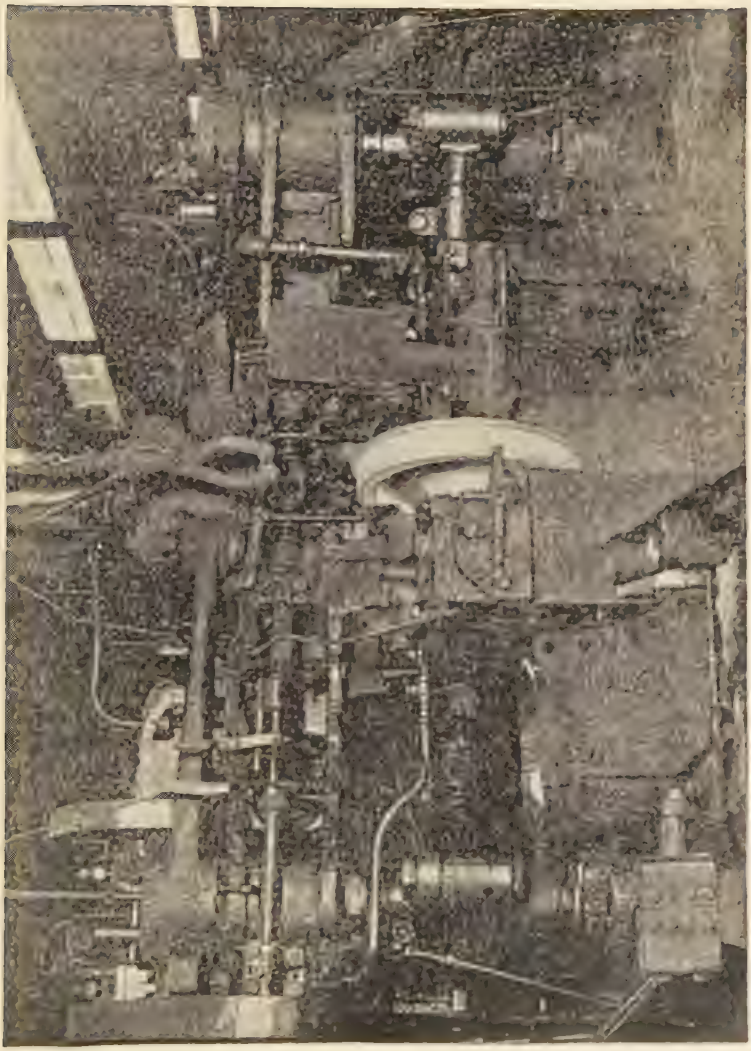


FIG. 183. View of One of the Older Mills Finishing a Wheel

will lie in parallel planes after the dishing, or coning, process. Two shelves attached to the housings in front of the tread and web rolls and separated by a space a little greater than the thickness of the wheel at the hub, gives a support for the wheel, which is mounted on a loosely fitting mandrel during the rolling. This mandrel is provided with removable bearings, which rest, unattached, upon the shelves, thus leaving the wheel free to move forward after the rolls have gripped it.

The Rolling Process: After the forged blank has attained the proper temperature for rolling, it is removed from the furnace and carried to the mill with a charging and drawing machine, where it is gripped beneath the rim by tongs suspended by a small jib crane standing on the housing above the rolls, or by a machine especially designed for the purpose. The wheel, held vertically, is guided between the two supporting shelves, and the mandrel is inserted through the punched bore. The crane tongs are then released, and the wheel, resting on the mandrel, is pushed back against the tread roll and into the position for rolling. The web and rim rolls are then brought to bear on the wheel, the latter rather lightly at first. The large driving motor is started, and the wheel is made to revolve by the action of the web rolls upon it. These rolls, working upon both sides of the web and the under side of the rim, force the metal back into the groove of the tread roll with considerable pressure, until this part of the wheel has reached the dimensions for which the mill is set, or the diameter desired, while the spread of the metal and the width of the rim is controlled by pressure applied to the four rim rolls. The diameter of the wheel is ascertained by means of a gauge, or caliper, one end of which is attached to the tread roll housing, so that it is moved simultaneously with this roll, in the same direction and through the same space. The other end of the caliper projects in front of the mill, and is provided with a hinged arm or pointer, so that it may be raised out of the way for inserting the blank or removing the wheel. The end of this pointer is curved toward the mill at right angles to its length. At the beginning of the rolling, the roller lowers this pointer to rest on the left hand shelf, in which position its curved end extends toward the tread roll and is opposite its line of contact with the wheel, the pointer having been adjusted so that the distance between its point and the tread roll is equal to the diameter of the wheel desired. With the rolling, the wheel increases in diameter and moves forward on the loose sliding mandrel until a circle on the center of its tread comes in contact with this pointer, when the roller stops the mill and spreads the rolls for the release of the wheel. During the rolling, jets of water are directed against the surfaces being rolled to remove the scale and give a smooth finish to the wheel. In addition to the water, a salt jet is also directed against the tread. The actual rolling process requires about one minute, so that the maximum capacity of the mill is more than 500 wheels per day of twenty-four hours. However, on account of the care exercised to assure a high quality of product, these mills are operated at only 50 to 60 per cent. of their capacity.

A. The Blank.

B. Blank after First Forging.

C. Blank after Second Forging.

D. Wheel, after Punching, Rolling and Coning.

FIG. 184. Sketches Illustrating the Manufacture of Car Wheels by the Carnegie-Schoen Method.

Effect of the Rolling: It will be observed that all the work of the rolling is concentrated upon the outer part of the web and the rim, where the additional refinement due to rolling is most needed. This refinement is very marked, as is shown by Brinell tests on sections of the wheel and by the visible difference in the structure of the metal between the hub and rim. This effect is most marked on the tread, where the hardness of the metal and closeness of grain can, no doubt, be considerably increased by rolling at low temperature or by chilling the metal by using an increased amount of water during the rolling. However, as such practice is likely to cause spalling, it is not employed by the operators. As machining the tread removes much of this super-refined metal, it would appear that the wheel rolled to a finish should be far superior in wearing properties to the machined wheel, on first run, at least. However, to insure absolute rotundity in all wheels, machining is necessary. Furthermore, although the mill practice on rolled to finish wheels is high, a greater or less number of the wheels require machining in order to eliminate slight surface defects.

Punching Web Holes and Coning: After the rolling, the wheel is taken on a buggy to a small press, where the web holes are punched, when these are required. This press is fitted to punch either two or four holes,

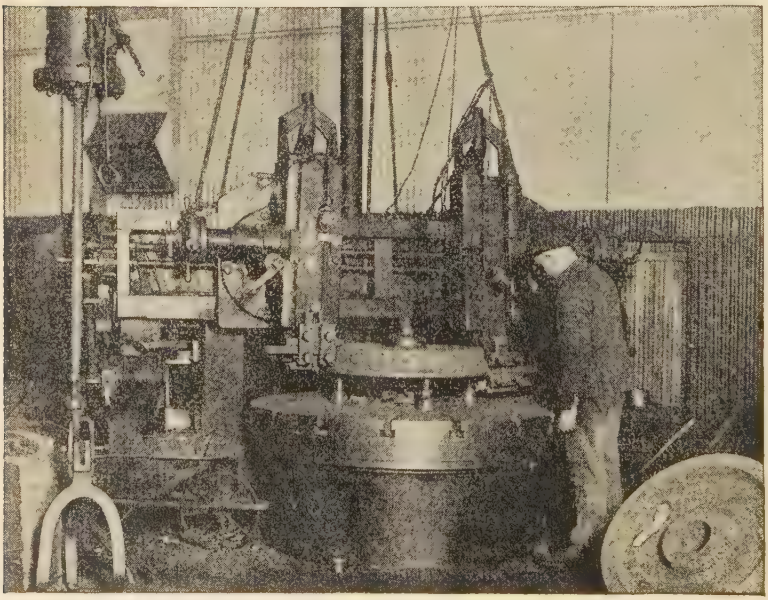


Fig. 185. Machining the Tread, Flange and Rim of a Car Wheel.

one and three-fourths inches in diameter, and equally spaced on radii of 8½, 9¼, 10, 11, or 12 inches, which are standard radii for all the different sizes of wheels. From the punching press, or from the rolling mill, if web holes are not required, the wheel is taken to the coning press. This press is provided with dies which conform to the exact contour of the finished wheel, the top die corresponding to the inside of the wheel. For preserving the rotundity of the wheel, the bottom die is surrounded with a series of tread blocks in the form of segments of a circle, while the top die is similarly provided with a tapered ring to fit over these segments. Thus, when the dies are brought together for coning, this ring slips over the outside of the segments and forces them firmly against the tread while the coning or dishing is being effected. As these blocks leave slight impressions on the tread where adjoining blocks meet, the wheel is turned through an arc of a few degrees and again subjected to the pressure, which removes all but traces of these marks, except in occasional cases where they are unusually deep. Upon removal from this press, the wheel is transferred to a special stamping press and hot stamped with the word Carnegie, a mill serial number, the heat number and the date, on the inner edge of the rim; then it is passed to the cooling bed.

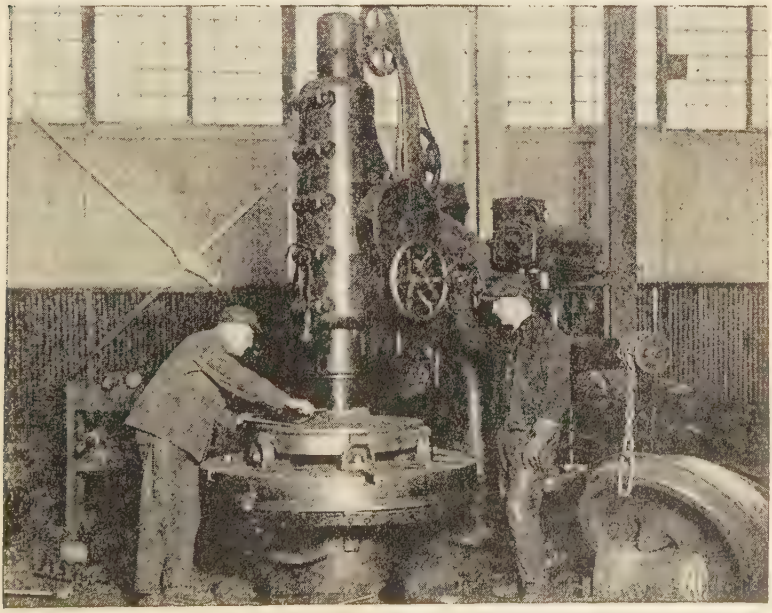


Fig. 186. Finishing the Hub of a Wheel.

Inspection of Carnegie Schoen Wheels is very rigid. When cold, the wheel is rolled to the inspection platform for its initial inspection. This inspection covers surface defects, location of the hub, rotundity of tread, and the size, which is measured in Carnegie Standard tape sizes. These tapes are graduated in eighth's of an inch, beginning with seven feet for a zero mark. The surface defects consist principally of overfills, underfills, slivers, scale pits, and block marks, and as they are seldom deep, they may be removed by machining. The tape size and all defects are plainly marked on each wheel, the former with a stencil, the latter in chalk. After this preliminary inspection, the wheels are machined as required to meet the specifications or remove the defects. On rolled to finish wheels, the machining consists of rough boring and facing of the hub. The wheels are then rolled back to the platforms for final inspection, which is even more rigid than the first. In this inspection the wheels are tested for size, eccentricity and size of bore, position and size of hub, thickness and height of flange, radius of throat, thickness of rim, coning, rotundity, and soundness. After being re-stenciled with tape size and marks requested by the customer, such wheels as come within the allowable tolerances are mated and sent to the shipping platform.

Heat Treating Car Wheels: Heat treating is a recent innovation in the manufacture of car wheels, and may be said to be still in the experimental stage. Owing to the irregular section of the wheel, quenching is a difficult process, because, if the entire wheel is quenched, the uneven cooling of the heavy and light parts set up stresses in the shape that result in the destruction of the wheel. In order to overcome this tendency, the Carnegie Steel Company's research department has developed a method whereby the rim only is quenched, after which the wheel, before the hub and web have cooled, is given a drawback at a suitable temperature under the lower critical range. If the hub and web are cooled in air after the quenching of the rim, the wheels show a dangerous tendency to crack by this method, also, hence the quick draw back. From an economical point of view, it would appear that the cheapest plan would be to quench the wheel on the rolling heat, but on account of unavoidable variations in the finishing temperature this treatment was found to be unsatisfactory. The wheels, therefore, are allowed to become cold after rolling and coning, when they are reheated above their critical range before quenching. This process is accomplished in a rectangular tank provided with rollers grooved to conform to the tread and flange and so placed in the tank that they support the wheel in a vertical position transverse to the tank, which contains enough of the quenching fluid to cover the rim only. With the rollers, which are mounted on a shaft connected to a motor, revolving, the wheel, at the proper temperature, is placed in position on the rollers, which immediately start the wheel revolving, or spinning, also. The spinning is continued until the rim becomes sufficiently cooled, when it is withdrawn and immediately given a draw back, as stated above. The process adds considerable to the cost of

the wheel, and though there are many wheels in service thus treated, and apparently with promising results, sufficient time has not yet elapsed to determine just to what extent the wheels are improved by the treatment.

The Forging of Circular Shapes: As previously indicated, only those circular shapes which are more than twenty-six inches in diameter can be finished by rolling on the Schoen mill. However, this plant, which represents the circular shape department of the Homestead works, produces a great number of smaller circular shapes by forging only. These smaller shapes include such articles as wheels for low type street cars; double flanged crane track wheels; automobile fly wheels; turbine discs; shaft couplings; pipe flanges; pistons for locomotives; gear rings; and gear blanks for automobiles, farm tractors, turbo generators, street cars, etc. In addition to these, a miscellaneous lot of circular shapes ranging in form from the most intricate sections to plain discs, and in sizes from ninety pounds to five hundred and even a thousand pounds are produced. For forming all these shapes, the same powerful presses are employed as are used in preparing the rolled wheel blanks, and in general the methods of forging are similar, with the exception that additional precautions in the removal of scale before forging are observed. In this connection it should be noted that forging will not produce the smooth finish obtained by rolling on the Schoen mill, and all forged articles requiring a smooth surface must be machined to finish.

CHAPTER XI.

FORGING OF AXLES, SHAFTS AND OTHER ROUND SHAPES.

SECTION I.

HOWARD AXLE WORKS AS AN EXAMPLE OF A FORGING SHOP.

The Plant and Its Equipment: Aside from the forging of armor plate and other articles required by our government, small wheels and a miscellaneous lot of shapes for its own use, the Carnegie Steel Company has restricted its market activity in the forging line to the manufacture of axles, shafts and similar heavy products. For these products the company operates a plant especially designed for the work, known as the Howard Axle Works, which may be taken here as an example of a modern forging plant. The essential equipment of the plant includes three continuous gas fired furnaces for heating the blooms, a twenty-four-inch roughing mill of two stands of rolls in tandem, ten 7000-pound and two 7500-pound double acting steam forging hammers, three gag press straighteners, thirty-two double cutting-off and centering machines, twenty-seven rough turning lathes, two finishing lathes, one boring lathe, two hollow drill machines, and a complete heat treating plant that will be described more in detail later. The forging limits of the plant as to size are as follows: Maximum weight, 3500 pounds; maximum length, ten feet; maximum diameter, fourteen inches; minimum diameter, three inches. As to arrangement, the layout of the plant provides for the most economical handling of the matrials. The blooms start in at one end of the plant and continue in one direction, progressing step by step through the various operations, until, upon arrival at the other end of the plant, they are in a form ready for shipment.

Precautions to be Observed in the Manufacture of Axles: As the failure of an axle in service usually results with serious consequences, great responsibility rests upon the manufacturer at all times to see that each and every axle is as nearly perfect as it is possible to make it. Before describing the processes of manufacture, it may be well to point out some of the things that may cause axles to fail, because the thing aimed at in developing a method of manufacture is the elimination of as many of the causes of failure as possible. There are many of these causes of failure, according to some writers upon the subject, but the majority may be traced to the following, which are to be looked upon as the chief sources of danger: 1. Pipe; 2. Segregation; 3. Unequal or improper heating·

4. Slag inclusions; 5. Forging strains; 6. Incipient cracks. From this list it is seen at a glance that some of these sources of danger are very difficult to eliminate and that the making of a good axle must begin with the making of the steel, itself. The other defects may be overcome by proper attention to details during the processes of rolling and forging the steel. Starting with the steel after it has been rolled into blooms, which must correspond in dimensions and weight to the size of the axles it is intended for, the various steps in the process of manufacture at these works are as follows:

Inspection of the Blooms: Located at Homestead, Pa., the Howard Works receives its steel from the Homestead Steel Works at Munhall. Here, before the steel is shipped to the axle works, the blooms are subjected to a rigid inspection. Those blooms that show any signs of pipe or insufficient discard at the blooming mill shears are rejected. Surface defects, such as seams, slivers and surface cracks, are carefully chipped out, and those blooms in which the defects extend beyond certain depths, or occur on the part that corresponds to the wheel seat are also discarded. Such blooms as pass the inspection are shipped to the axle works, where they are stored under cover until needed.

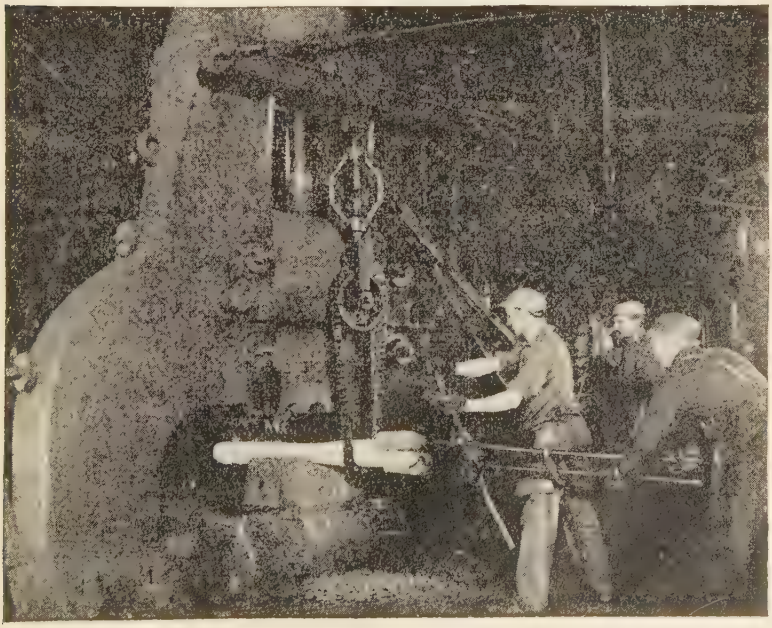


FIG. 187. View of 7000-pound Steam Hammer in Operation, Forging an Axle.

Heating the Blooms: The proper heating of the blooms for forging requires that they be uniformly heated throughout and be brought gradually to the forging temperature, which should be kept as low as possible and yet permit the work to be done. The advantages of a low finishing temperature in securing maximum grain refinement is readily understood. The importance of heating slowly is also realized, when it is pointed out that rapid heating may cause the outside of the bloom to become somewhat hotter than the core, which condition would prevent uniformity in grain structure and in the flow of the metal during the subsequent rolling and forging operations. Slow heating gives the heat a chance to "soak" into the bloom, thus giving that uniformity in temperature from center to surface so necessary to secure a finished forging of the best quality. As to the proper temperature, the manufacturer has always had to depend upon the eye and judgment of the trained heater in the past, and must continue to do so to a great extent in the future. The use of pyrometers does not replace this human element, because the pyrometer records the temperature of the furnace and not of the steel, particularly in the case of the continuous furnace. The rate of heating is fixed by the type of furnace. At these works, therefore, the continuous furnace is used because this type heats up the steel very gradually. The bloom is placed in the furnace at the cold end and is slowly pushed toward the hot end, so that it reaches a full forging temperature only a short time before it is drawn from the furnace.

The Rolling and Forging Operation: Having been brought to the proper temperature for forging, the blooms, within a certain range of sizes, are pushed out of the hot end of the heating furnaces upon a conveyor, which serves all three furnaces, and are carried by it to the rolling mill. This mill consists of two stands of rolls in tandem, as previously stated. Each stand is provided with four passes cut to take four different sizes of square blooms. These sizes are 6½, 7½, 8 and 8½ inches. The passes are shaped to round off the corners of the bloom, to secure which result is the main object in the use of the mill. The reduction in cross sectional area due to the rolling varies from 3½ per cent. to 5 per cent. From the mill, a roll table distributes the blooms to the hammers, which are arranged in two rows, one on each side of the table. Adjustable deflecting rails built in the side guards of the table serve to divert the blooms to small receiving tables, of which there is one for each hammer, and leave them in positions to be most conveniently grasped by the hammer tongs, which are suspended from cranes. The tongs having been quickly clamped on, the bloom is swung around between the forming dies of the hammer. These dies are provided, when desired, with two or more grooves; one, the plain groove used to do the greater part of the forging, is located directly under the piston rod, while the other grooves, used to form special sections, such as the journals, are placed beside the plain groove. The forging is begun at the middle of the bloom, which is rapidly reduced by heavy blows of the hammer, the forging progressing toward the free end of the bloom. Here,

by the special grooves in the die, the journal or other special section is formed by a few strokes, when the piece is again placed in the plain groove, and the forging is smoothed up and brought, by light strokes of the hammer, to correct diameter, which is determined by caliper. The tup is then brought to rest upon the axle, which is held between the dies while the tongs are released, and those on the opposite side of the hammer are made fast to the finished end. The other end of the axle is then forged down like the first, except that, in addition to diameter, the length is also fixed. The crane is then swung around, and the axle is placed on the cooling bed, where it is supported about three feet above the floor by two rails, which arrangement allows it to be cooled uniformly by the air. The average reduction in cross sectional area under the hammer is about 50 per cent. Forgings requiring blooms larger than eight and one-half inches are reduced entirely by hammer. Two crews, each made up of a hammerman, who has charge of the forging, and three helpers, and one hammer driver, are assigned to each hammer. The crews work alternately, each crew completing one axle at a time.

Advantages of the Method: Aside from the increased tonnage made possible by the rapidity of the work, the method of forging employed at Howard presents many advantages which bear directly upon the quality of the product. The rolling mill, which accomplishes only a small fraction of the total work done upon the axle, is a great help to the hammers. By rounding off the corners of the bloom, it practically eliminates all danger of forming hammer laps, and permits the forging to be accomplished in the shortest time possible. Hence a low initial temperature can be used for

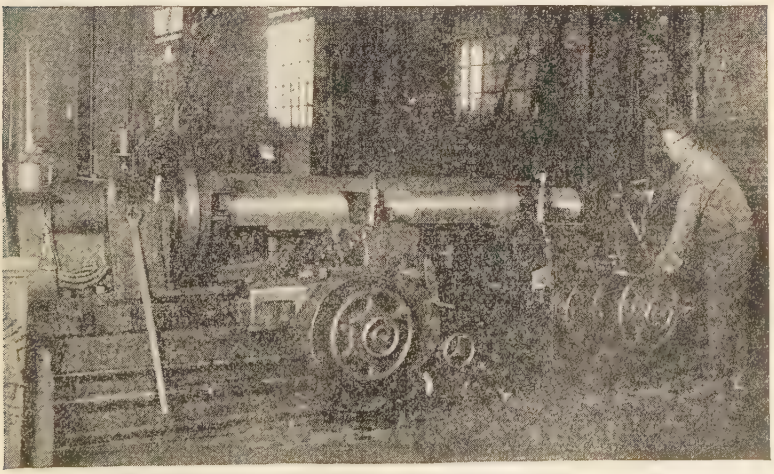


Fig. 188. Machining an Axle Rough Finished all over.

forging, and the work can be completed at a more uniform temperature. This uniformity of the finishing temperature is a very noticeable feature at Howard. Thus, in observing closely various axles at different stages of the forging operation the eye can detect little difference in temperature between those axles on which the forging has just begun and those that are being finished. That this rapid method of forging on one heat is far superior to the old method of forging on two heats is apparent, because it not only promotes greater uniformity in individual axles but eliminates, to a far greater degree, the variation in different axles.

SECTION II.

FINISHING PROCESSES FOR FORGINGS.

Straightening: Except in the case of heat treated axles, and driving and trailing axles, the next step after the forging is the straightening, which is accomplished by means of gag presses. From the cooling beds the forgings are carried forward by overhead cranes to similar beds in front of the presses. Here each axle is inspected for straightness, and those that require it are straightened. Heat treated axles are straightened after being treated, but driving and trailing axles too large to be straightened by the gag press are straightened under the hammer, when required.

Cutting-off and Centering: After passing the inspection for straightness, the forgings are moved forward by overhead cranes and distributed to the cutting-off lathes. These lathes are double combination cutting-off and centering machines, and are designed to work on both ends of the forging at the same time. Upon being inserted in this machine, the forging is grasped at the wheel seats by adjustable revolving centering clamps, which hold it firmly to the central axis of rotation, while two cutting tools, placed one at each end and adjusted to the correct length, are brought to bear and cut off the excess metal at the ends. In this cutting, a tolerance of one-eighth inch over length and nothing under is permitted. When these tools have cut to within about one-half inch of the center, they are run back out of the way, the pieces of excess metal are detached with a sledge, and with the forging still held by the centering clamps, the revolving centering tools are brought to bear at each end. These tools are shaped to cut a 60 degree cone-shaped centering hole, five-eights inch in depth, one and one-eighth inch in diameter at the top, and with a clearance hole

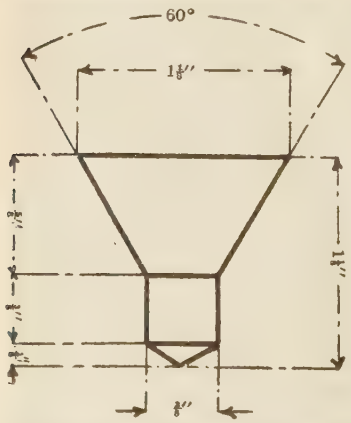


FIG. 189. Carnegie Standard Centering for Axles.

for points at the bottom one-half inch in depth and three-eighths inch in diameter. When axles are ordered to be smooth forged only, the operation of cutting off and centering completes the work done by the mill. On such axles some excess stock is necessarily left on those parts that are to be finished later. This allowance on car axles is generally one-half to three-fourths inch over the finished diameters of the end collars, journals, and dust guards, and one-fourth to three-eighths inch on wheelseats.

Rough Turning: On account of the saving that can be effected in handling and transportation of excess weight, it is a decided advantage to both the customer and the shop, especially to the latter, that all rough turning be done before shipment is made, as it is only by rough turning that certain flaws can be detected. Rough turned material falls into two classes, known as "rough turned on journals and wheelseats," and "rough turned all over." Axles of the first class are put into service with the center portions between the wheelseats smooth forged to size. In the case of axles rough turned all over, the center portions are forged slightly over size to provide for the metal removed in turning to size. In the case of car axles or other axles with a tapered body, this metal is removed at the same time (or after) the journals and wheelseats are rough turned, in a special lathe provided with two tools controlled by a former-bar whose contour is inverse to the middle portion of the axle. In finishing rough turned axles, the wheelseats are finish-turned only, while the dust guards, journals and collars are finish-turned and burnished, and in order to provide the excess metal required for this work, these parts are rough turned one-eighth inch over size on their diameters.

Bored Axles: Owing to the many apparent advantages arising therefrom, the practice of boring large axles and forgings longitudinally through the center is being advocated more and more strongly. These advantages are briefly discussed under the following headings:

1. **Piping,** it will be recalled, was given as one of the causes of failure. While the Carnegie Steel Company, by a generous discard and close inspection, aims to eliminate this defect, yet it is possible that some forms of piping, notably compound pipes, may escape both the discard and the inspection, and remain in the axle as a menace to safety. Boring gives the inspectors a chance to detect this hidden pipe.

2. **Segregation** was given as another source of failure. This defect cannot be entirely overcome in the manufacture of steel, and inspection is no safeguard against it. But as the area of greatest segregation lies about the central axis, boring a hole of proper size longitudinally through the center should, and does, remove the greater part of all the segregated material from the axle.

3. **Strength and Weight:** The central portion of an axle removed by boring is really a non-essential part so far as strength is concerned.

The transverse strength of solid rounds is proportional to the cubes of their diameters, but boring a round axle or shaft lengthwise through its center does not reduce its strength in the ratio of the cubes of the diameters of the solid round and of the part removed. If such a bore be made, removing a cylindrical portion concentric with the long axis of the axle, the removal of this portion decreases the strength of the axle by an amount that is less than the strength of an isolated cylinder of the same size, because the extreme fibers of this central portion, in the case of the solid axle, are, under a load, stressed proportionally less than the fibers at the periphery of the axle. With this difference in fiber stress given proper consideration, it may be shown mathematically that the actual reduction in strength due to boring, expressed fractionally, is the same as the fourth power of the ratio of the diameter of the bore to the diameter of the original round. So, for example, if a three-inch bore be made in a six-inch axle, the theoretical loss in strength is but 6.25 per cent.; in an eight inch axle, 1.978 per cent. These figures represent the loss in strength provided the center is as strong as the outer portion, which condition may or may not be true in ordinary practice. However, this factor need not be considered, as the material near the center may be considerably weaker than that in the outer cylinder and still be strong enough to balance the smaller stress in the central portion of an axle under load. Nevertheless, the axle with the bored center may be safer than it would have been solid, provided it contained much segregated material or the remnant of a pipe,—conditions that favor the formation of internal cracks, especially under vibratory stresses. The chief advantage of boring is to be found in the relation between the loss in strength and the loss in weight. In this connection it will be observed that, whereas the loss of strength varies according to the ratio stated above, the loss in weight varies as the squares of the diameters of the original solid round and the removed portion. Referring to the example cited above and applying these laws, the reader will find that, while, in the case of the six- and eight-inch axles with the three-inch boring, the loss in strength is 6.25 per cent. and approximately 2 per cent., respectively, the loss in weight is 25 per cent. for the first and 14.3 per cent. for the second.

4. **Boring and Heat Treating:** As an aid in heat treating, especially in quenching and tempering, or toughening, boring is of great importance. In heating, it permits the heat to be absorbed much more rapidly, and in quenching, the heat is more rapidly removed than in solid pieces, with the result that the structure is more uniform. Furthermore, contraction and expansion strains are largely overcome, and skrinkage cavities in the center are avoided. The American Society for Testing Materials specify that all forgings over seven inches in diameter that are to be quenched shall be bored. The diameter of the hole bored should equal or exceed 20 per cent. of the largest diameter of the forging exclusive

of collars or flanges. Howard Axle Works are equipped to bore holes either two or three inches in diameter.

The Heat Treating Plant is housed in the same building with the hammers and lathes and consists of two furnaces for heating with the forgings in a horizontal position, one furnace for heating the material in a vertical position, one water quenching tank, one oil quenching tank, and all the necessary supplemental equipment for handling and testing the material.

The Furnaces: The inside working space of the two furnaces of the first type are each twenty-one feet in length and eight and one-half feet in width, and are designed to heat uniformly to a height of about four feet above the bottom. They are provided with removable bottoms of the car type, which much facilitates the charging and drawing operations. This bottom is moved into and out of the furnace by means of a toothed rack attached to the bottom of the car and a stationary pinion actuated by an electric motor, the car itself resting on rollers that move over a double track. The doors of the furnace are of the vertically lifting type, and are hydraulically operated. These features, together with the close proximity of the quenching tanks, permit the drawing and quenching of a charge in the quickest possible time, less than a minute being required to transfer a charge from the closed furnace to either of the quenching tanks. The measures taken to secure uniform heating are particularly noticeable in this furnace. The furnace is of the reversing flame type, in which gas is employed as fuel, and is heated by means of burners placed at space intervals of less than two feet along each side, thus permitting the temperature at any point in the furnace to be controlled to a nicety. At the top, the furnace is closed with a roof, arched from side to side, while, inside, high bridge walls extend along in front of the gas burners to prevent the flames from impinging upon the charge. In order that the entire surface of the material may be exposed to heat of the same intensity, the charge is supported at a height of about eighteen inches above the floor of the car bottom by two steel rails that extend the entire length of the car. These rails are spaced about four feet apart and are supported by castings in the form of four-legged stools. The floor of the car bottom is constructed of brick laid upon a bottom of steel plates, and is of such thickness as to give ample insulation from the heat of the furnace. The bottom is made to fit the furnace neatly, and the escape of hot gases from the heating chamber is prevented by means of sand seals. The construction of the furnace for heating the charge in a vertical position is somewhat like that of a soaking pit. It has a capacity of about six axles and sufficient head room for maximum lengths of ten feet. In operating this type of furnace, the axles are loaded on a cast steel rack, which is specially designed to support them in a vertical position, and are lowered through the top into the furnace where they are maintained in a vertical position throughout the heating operation. This furnace is seldom used,

as more satisfactory operating conditions are obtained by using the other type. For taking temperatures the Siemens Water pyrometer is used exclusively.

The Quenching Tanks: For use in connection with these heating furnaces, the plant is equipped with one water quenching and one oil quenching tank. These tanks are both placed as near as possible to the furnaces, the water tank being directly in front of one of the furnaces of the horizontal-heating type. This tank, approximately twenty-five feet long, twelve feet wide and fourteen feet deep, is of the sub level type and is constructed of concrete. When in use, the water level lies about two feet above the floor of the shop. So, an ample volume of water is supplied for any charge it is practicable to handle, and, in addition, provision is made whereby fresh water may be introduced during the quenching operation at one corner of the tank and the excess conducted away at the diagonally opposite corner, both inlet and outlet being located near the top of the tank. Two beams extending the full length of the tank and supported about two feet above the bottom, prevent the charge from resting on the bottom when lowered by the crane, thus securing more uniform cooling. The oil quenching tank is some sixteen feet in length, nine feet in width, and ten feet in depth, inside. It is made in two parts—an oil container and a cooling jacket. The container is made of steel plates and is set within the cooler, which is constructed of concrete and is about twenty inches longer and wider than the container, so that a space of about ten inches separates the walls of the two vessels. This space is kept filled with cold water, which serves to prevent the temperature of the oil rising too high during quenching, and to cool it down rapidly after each charge.

The Testing Equipment includes all the latest devices for testing materials. In the shop, two hollow drill machines for cutting out tests are provided, and as all heat treated axles are given individual shock tests, a drop testing machine for giving these proof tests is also located here. Two drop testing machines, adapted for testing axles in accordance with standard specifications are provided. Other physical tests are made in the physical laboratory, which is equipped with one planing, one turning, one pulling, one torsional, one bending and one Brinell machine, and all the supplemental appliances for accurate testing.

Advantages of Heat Treating Axles: While the proper heat treating of axles is accomplished with some difficulty on account of their size, and is attended with great danger if improperly done, yet with proper equipment, great care and good judgment, born of knowledge and experience on the part of the operator, the dangers may be eliminated, and decided advantages result therefrom. It is the only way in which the grain structure can be refined and made uniform, and in doing this all the evils due

to variations in the grain, which result from the heating and working of the bloom, are overcome, as well as forging strains. But greatest of all these advantages is the improvement in mechanical properties effected through correct heat treatment. It offers the only positive means of markedly increasing the strength and wearing properties of axles without in any way increasing their weight—a thing that is much desired under modern conditions of traffic.

PART III.

THE CONSTITUTION, HEAT TREATMENT AND COMPOSITION OF STEEL.

Introductory: It is the desire in this part of this book to center the interest of the reader chiefly about the heat treatment of steel. So much progress in the study of this subject has been made in recent years that many are inclined to look upon it as something new. That remarkable changes in the physical properties of a given steel can be brought about through the agency of heat alone has been known for many years, but until 1890 the subject had received very little attention from scientists. Up to that time both the scientific knowledge about the subject and the technical application of the art of heat treatment were very limited, being confined for the most part to the making of tools and a few specialties. The development of the automobile, the airplane, and other machines, the different parts of which are required to be light and at the same time suitable for the usages to which the parts are subjected, gave rise to demands for steel of great strength combined with various other specific properties. These demands directed the attention of investigators to heat treatment because it was found that this was the only means of meeting these requirements. Practically all alloy steels must be heat treated in some way, and few steels in their natural state will give their full value in service, so that the various combinations of static and dynamic strength and wearing qualities required can be obtained in their highest degree only by adjusting and correlating both the chemical composition and the heat treatment. Just as certain chemical components intensify one set of properties, and others another set, so the heat treatment may be changed to develop different qualities in a similar way. Thus, by combining the proper chemical composition with the proper heat treatment, there results a product possessing in the highest degree the properties most desired for the work the steel is to do. So it is evident that the intelligent application of heat treatment to secure the best results requires a thorough knowledge, on the part of those supervising the work, of the composition of the steel and the effect of the various elements that are to be found in all steels or that may be added as alloys to produce the special steels. Again: Heat treatment consists in heating and cooling steel under conditions that will produce the desired change or changes in physical properties, and embraces the three processes of annealing, hardening, and tempering, to which may be

added the special processes known as "process annealing," "patenting," "case hardening," etc. The remarkable changes in properties that may be obtained, together with the phenomena observed during heating and cooling, all connote vital changes that are brought about by the heat treatment. As no change in composition of the metal takes place, the cause for the phenomena must be sought in changes of arrangement or condition of the constituents of the steel itself. Another pre-requisite, then, to the study of heat treatment is the study of the structure and constituents of steel, a thorough knowledge of which is essential to any understanding of the subject, whatever. For this reason, the study of heat treatment should be prefaced by a brief summary of the knowledge concerning the structure and constitution of steel.

Before beginning this study, however, the student should understand that part III of this book is intended merely as an introduction to the study of metallography, heat treatment and composition of steel. Those who desire a further knowledge of these valuable and fascinating subjects are referred to such authorities as Albert Sauveur[1], whose plan of developing the subject is closely followed in this study; H. M. Howe[2], whose iron carbon diagrams are used herein; D. K. Bullens[3], whose practices in heat treatment are frequently referred to; and Zay Jeffries and R. S. Archer[4], whose theory of hardening, based upon X-ray analysis of metals, has attracted much attention.

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[1]See the Metallography and Heat Treatment of Iron and Steel, Published by Sauveur and Boylston, Metallurgical Engineers, Cambridge, Mass.

[2]See Iron, Steel and Other Alloys, and The Metallography of Iron and Steel. Both published by McGraw-Hill Book Company, Inc., 239 West 39th Street, New York.

[3]See Steel and Its Heat Treatment, Published by John Wiley & Sons, Inc., New York City.

[4]See The Science of Metals, Chap. XII. Published by McGraw-Hill Book Company.

CHAPTER I.

THE CONSTITUTION AND STRUCTURE OF PLAIN STEEL.

SECTION I.

STEEL AS AN ALLOY OF IRON AND CARBON.

The Constituents of Steel: Steel is not a single element or compound, but a complex artificial product, composed of many elements held in the solid mass as a mechanical mixture of alloys and chemical compounds with the element iron. In ordinary steel, these elements are iron, carbon, manganese, phosphorus, sulphur, silicon and oxygen, with traces of nitrogen, hydrogen and other elements, such as aluminum, copper and arsenic. Of these, all are to be considered as impurities except carbon, which is an essential ingredient, and manganese, or other elements added for a definite purpose. For the sake of simplicity and brevity only pure steel, consisting of the two essential elements, iron and carbon, will be considered in this chapter. Even in this case steel is found to be an aggregate made up of mineral-like components, some of which are visible only with the aid of the microscope after the surface of the specimen has been highly polished and etched with dilute acids or other corrosive mixtures which affect the various constituents in different ways. To the structure thus revealed by the microscope the term micro-structure is given, to distinguish it from the macroscopic structures, or those visible to the naked eye; and to the different constituents mineralogical names have been applied. Thus, in pure steels which have cooled slowly from a high temperature, three distinct constituents are recognized. They are called ferrite, pearlite, and cementite, and in the different steels will vary in amount according to the carbon content.

Ferrite is the term applied to pure iron, i. e., carbonless iron, when it is considered as a microstructural constituent of steel. It is soft, ductile and relatively weak, having a tensile strength of about 39,000 pounds and an elongation of 30 per cent. or more in 8 inches. Under ordinary conditions of heating and cooling it exhibits practically no hardening power, but that it possesses this power as an inherent property is indicated by the fact that if pure iron is heated to, or nearly to, its fusion point and cooled with exceeding rapidity, it becomes markedly harder. As a conductor of electricity it holds an intermediate position among the common metals, its conductivity being about 17 per cent. of that of pure copper. It can be easily magnetized, but quickly loses most of its magnetism on removal of the magnetizing force. Under the microscope it appears white

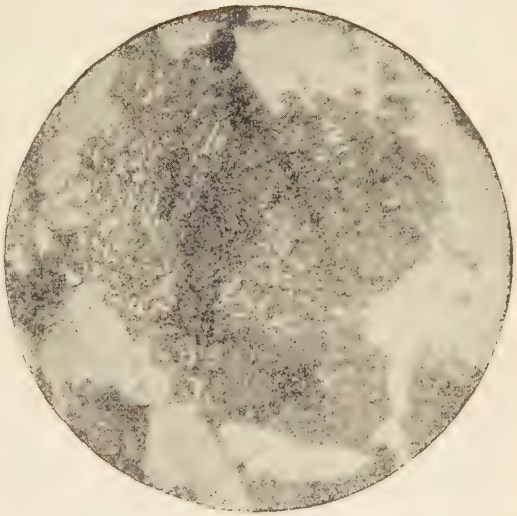


Fig. 190. Photomicrograph showing a grain of pearlite surrounded with free ferrite as a net work. Specimen taken from annealed steel containing carbon .48 per cent. and manganese .54 per cent. Magnified 750 diameters.

Etched first in 5% alcoholic picric acid for eight seconds, then in 5% alcoholic nitric acid for five seconds. White area represents ferrite. On account of a too rapid rate of cooling, the pearlite is not fully developed. Compare with Figs. 112, 113, 115 and 201.

Fig. 191. Photomicrograph of a specimen of steel containing carbon to the extent of 1.50 per cent. The excess cementite is here seen in the form of spines, or needles.

Magnified 100 diameters. Etched for eight seconds in five per cent. alcoholic picric acid and for two seconds in five per cent. nitric acid, making the free cementite, which stands in relief, brilliant white in color.

Figs. 190-191. Photomicrographs illustrating the micro structure of Steel. (Photographs prepared by O. M. Ash, Portland office, U. S. Steel Products Co.)

in color after being etched with dilute alcoholic nitric or picric acids. It is best seen in slowly cooled steels in which the carbon content is less than .50 per cent. In such steels it appears as a network surrounding bodies of pearlite, another constituent of steel to be described shortly.

Cementite: As already stated, iron and carbon are the essential elements in plain steel, and of these carbon may be termed the controlling element. When steels are cooled slowly from high temperatures, from the molten state, for example, all the carbon is found combined with a definite amount of iron in the form of a carbide of iron corresponding to the chemical formula Fe_3C. This compound consists of carbon, 6.67 per cent., and iron, 93.33 per cent., and it is known micrographically as cementite. Any excess iron is practically free of carbon at atmospheric temperatures and remains as ferrite in steels that have cooled slowly. Little is known about the properties of cementite except that it is very hard and brittle. Indeed, it is the hardest component of steel, and will scratch glass and feldspar but not quartz. It is about two-thirds as magnetic as pure iron under an exciting current. After polishing the surface of steel, it stands in relief, and is brilliant white after etching with dilute hydrochloric or picric acids. It occurs free in ordinary steels of more than .85 per cent. carbon, in which it appears as a network or as spines and needles. It takes its name from cement steel, made by the cementation process, which contains a great deal of this carbide, Fe_3C.

Pearlite: One of the most remarkable characteristics of cementite and ferrite is their power of forming the conglomerate known as pearlite. During the process of slowly cooling steel from higher temperatures, say above 1000° C. (1832° F.), it has been found that cementite and ferrite are liberated and form, at about 700° C. (1292° F.), a mechanical mixture made up of definite amounts of each and in the proportion of about seven parts ferrite to one part cementite, so that the resultant conglomerate will contain approximately .85 per cent. carbon. This constituent then consists of interstratified layers or bands of ferrite and cementite, and is called pearlite on account of its resemblance to mother of pearl. While pearlite commonly occurs in slowly cooled steels in the lamellar formation, composed of alternate layers of ferrite and cementite, it may under different rates of cooling and dependent on the relative amounts of ferrite and cementite present, exist in other formations, or phases, of which some authorities have recognized at least four, making in all five modifications, as shown in Fig. 201. Normal pearlite has a maximum tensile strength of about 105,000 pounds, and an elongation of about 10 per cent. in two inches. It is regarded as a separate and distinct constituent of steel because it forms distinct masses or "grains," always contains this definite percentage of carbon and, in carbon steel cooled slowly, is always formed at a definite temperature.

Manner of Freezing of Solutions and Alloys: In order to clarify the explanation of the formation of pearlite, it is necessary to digress to

the extent of explaining some of the freezing laws of solutions. A study of the freezing of solutions has shown that they fall into two classes, namely, those in which the ingredients in solution in the liquid state remain in solution in the solid state and those in which the state of solution is not maintained in the solid state, that is, those in which the ingredients separate on freezing.

An Example of the First Class of Solutions: One of the best examples of the first kind of solution is a mixture of gold and silver. If quantities of these two metals be placed in a vessel and heated until they melt, a homogeneous mixture, or a liquid solution, results; and if this mixture be allowed to cool to the solid state, it is still homogeneous, that is, it is a solid solution. A study of many mixtures in which the proportions of gold to silver are varied shows that freezing begins at a different temperature for each mixture. Pure gold freezes at 1062° C. and pure silver at 961° C., and the freezing points of the mixtures occur between these two points. Unlike the pure metals, however, these mixtures do not solidify completely at a constant temperature, but their freezing is prolonged through ranges of temperature. These facts, definitely determined by experiment, may be represented by a diagram, or curve, such as the following, in which the ordinates represent temperatures and the abscissae the percentage of gold or silver or both.

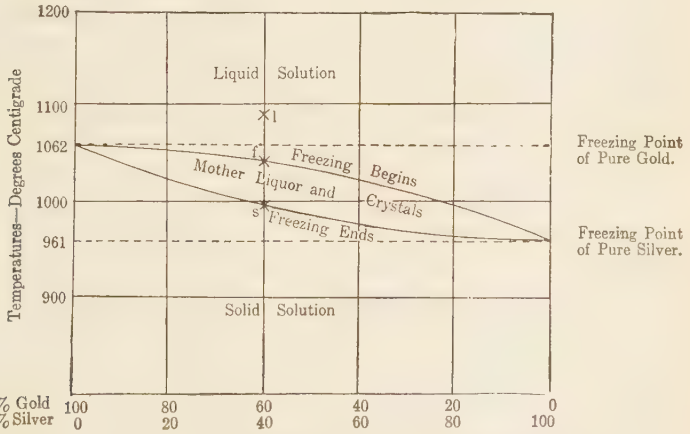


FIG. 192. Diagram of the Freezing of Liquid Gold-Silver Alloys.

To illustrate further, suppose 60 oz. of gold be mixed with 40 oz. of silver, and the whole heated to a temperature of 1090° C. The locus of this point would be at "l" in the region of the liquid state. If now this molten solution be allowed to cool slowly, crystallization will begin at "f," about 1041° C., and end at "s," about 990° C. Although as a matter of fact the first crystals formed will contain more gold than the liquid,—the proportion being, in this case, about 90 parts gold to 10 parts silver,—

and the last, more silver than the liquid, the average composition of all will be the same, namely, 60 per cent. gold and 40 per cent. silver. Furthermore, while solidification is going on, a process of diffusion is also taking place, which tends to adjust the composition of each individual crystal, bringing it nearer that of the average. Thus, while the composition of the solid body as a whole varies slightly, each crystal, or any small part of the body, is practically homogeneous and made up of a mixture of gold and silver, so intimate that they are not distinguishable.

Example of the Second Class of Solutions—Salt and Water: It is a well known fact that a solution of common table salt freezes at a lower temperature than pure water. This lowering of the freezing point, or rather the temperature at which freezing begins, varies with the proportion of salt to water until this proportion has reached the definite limit of 23.5 per cent., when any further addition of salt causes the point at which freezing begins to rise. This lowest temperature, at which the solution containing 23.5 per cent. of salt freezes, is—22° C. These facts are represented by the diagram of Fig. 193.

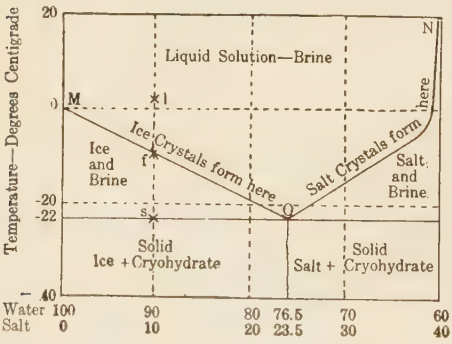


FIG. 193. Diagram Representing the Freezing of Solutions of Salt in Water.

Two or three examples will suffice to explain the freezing of solutions containing varying amounts of salt, and any other points about the diagram that may not be clear. Thus, suppose a solution containing 10 per cent. of salt is at a temperature indicated by "1". Although water freezes at 0° C., the temperature of this solution must fall to the point "f," about—10° C., before freezing begins. Here, unlike the solution of gold and silver, crystals of pure water begin to separate from the solution. The separation of these crystals has the effect of increasing the percentage of salt in the mother liquor, so that the separation of the water crystals continues only so long as the temperature is being lowered. Furthermore, if the rate of cooling has been uniform down to the point "f," a marked retardation takes place here, because the heat of fusion of the water must be removed before ice can be formed. With the removal of this heat, however, and that necessary to lower the temperature of the remaining solution, the separation of ice crystals continues, causing a concentration of salt in the mother liquor that bears a definite relation to the temperature as indicated by the line M O. Finally, when a temperature of —22° C. is reached, the mother liquor, which now contains 23.5 per cent. of salt, freezes as rapidly as the

heat of fusion is abstracted. When all this liquor has solidified, the temperature of the solid mass will continue to fall uniformly in a manner similar to that before freezing began.

If instead of the weak solution, a strong brine containing more than 23.5 per cent. of salt is substituted in the experiment just described, it is found that, just as ice separated along the line MO., salt crystals separate along the line NO, until the temperature —22° C. is reached and the mother liquor contains 23.5 per cent. of salt. This liquor then freezes as described before. When these facts were first observed, it was thought that the mother liquor that is the last to freeze was a hydrate of sodium chloride of the formula $NaCl.10H_2O$ and was called, therefore, the **cryohydrate,** cold hydrate, meaning a hydrate that could exist in the solid state only at low temperatures. It has since been shown that these cryohydrates are not chemical compounds, though they have a definite composition, but are mechanical mixtures made up of crystallized salt and ice in intimate contact.

Lead and Tin Solutions as Another Example of the Second Kind of Freezing: Many of the fused alloys exhibit the same phenomena in freezing that saline solutions do, showing that their constituent metals form a solution when in the liquid state but that they are wholly or partly insoluble in one another in the solid state. As an example of such an alloy, that of lead and tin is most convenient for study. To cite a specific example, let a mixture composed of 30 per cent. tin and 70 per cent. lead be heated to a temperature of 350° C. As this temperature is above the

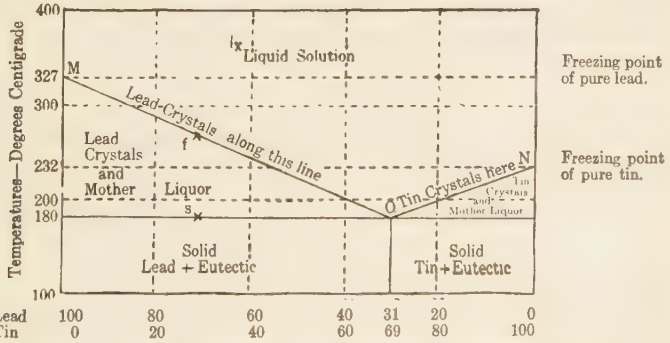


Fig. 194. Diagram Illustrating the Freezing of Lead-Tin Alloys.

fusion points of both lead and tin, which melt at 327° C. and 232° C., respectively, it is sufficiently high to insure that the mixture will be completely fused. Now, as this solution cools down, no crystallization takes place until a temperature of about 270° C. is reached, when crystals of almost pure lead begin to separate, making the remaining solution poorer in lead but richer in tin in the same way as the ratio of salt to water

became greater during the freezing of the weak saline solution. Likewise, as in the case of the salt solution, the separation of the lead causes a retardation of the rate of cooling, showing that heat is evolved thereby; and the freezing point of the mother liquor becomes lower, so that no further separation of lead takes place until more heat is abstracted. If the cooling be continued, however, the separation of the lead will also continue, and if proper measures be taken, a number of loci may be obtained of the cooling curves for alloys of different composition, which, when plotted, give the curve M O as represented in the diagram of Fig. 194.

When the cooling and the accompanying separation of lead has reached the point O., corresponding to a temperature of 180° C. and 31 per cent. of lead, or 69 per cent. tin, in the mother liquor, the whole mass becomes solid, forming a banded structure composed of minute crystals of lead and tin and corresponding to the cryohydrate of salt and water, but called, in the case of alloys, **eutectic alloy,** which signifies easily melted alloy. To the right of the point O, tin separates along N O like lead along M O. This manner of freezing, where one metal separates alone, is known as **selective freezing** to distinguish it from the kind of freezing illustrated by the gold-silver alloys, which, since both metals separate together, is known as **non-selective freezing.**

The Iron-carbon Eutectic: Coming now to a consideration of the iron carbon alloys, the student finds that the freezing of alloys of these two elements presents phenomena that are like those of both the gold-silver and the lead-tin alloys. The freezing of these alloys is represented by the following diagram, from which it is seen that the carbon content of the eutectic alloy is about 4.30 per cent. Therefore, when alloys that contain more than this amount of carbon are cooled from temperatures above the line M O N, carbon in the form of graphite separates along N O until the point O is reached, when the eutectic solidifies. Naturally, the reader would expect a similar separation of iron along the line M O; but it is here that the freezing of the solution produces phenomena similar to the freezing of gold-silver alloys, for it is found that, instead of pure iron separating, a definite mixture, or alloy, containing approximately 2.0 per cent. carbon and called **primary austenite,** separates from all mixtures in which the carbon content is two per cent. or more. By drawing in the vertical line A D, corresponding to about 2.0 per cent. carbon, this diagram is divided into two parts. The part to the right of A D shows the freezing of the iron carbon alloys to be like that of the lead-tin alloys, that is, selective, while that part to the left of A D shows that the freezing of all iron-carbon alloys whose carbon content is less than 2.0 per cent. is non-selective and analogous to the freezing of the gold-silver alloy. For example, suppose an iron-carbon alloy containing 1.0 per cent. carbon to be at a temperature of 1500° C. It is in the liquid state and represents a homogeneous mixture of iron and carbon, or a solution of carbon or an iron-carbon compound in iron. If now this solution is allowed to cool, crystal-

lization will begin when the temperature indicated by the corresponding point "f" on the line M O is reached, and will continue up to the point "s" on the line M P, when the solidification will have been completed. As in the case of the gold-silver alloys, the first crystals formed are richer in iron and the last richer in carbon than the liquid, but diffusion takes place so that the metallic body is made up of homogeneous crystals containing 1.0 per cent. carbon. This solid solution is also known as primary austenite. Because of this difference in the freezing of the iron carbon alloys between those containing more than 2.0 per cent. carbon and those containing less than 2.0 per cent. carbon, the carbon content of 2.0 per cent.

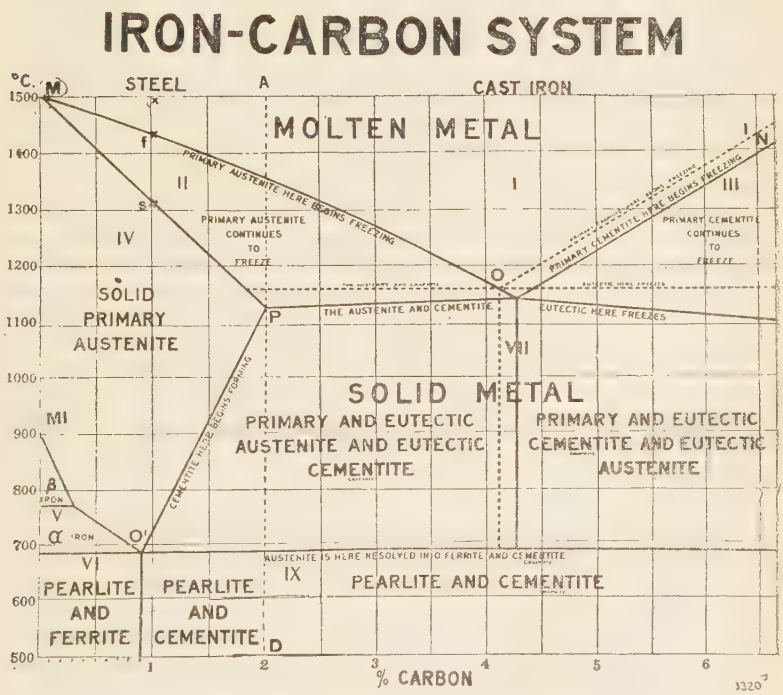


FIG. 195. Diagram Demonstrating the Freezing and Cooling of Iron Carbon Alloys. After H. M. Howe.

may be considered as the dividing line between steel and pig iron; consequently, this study is concerned mainly in the changes that occur in alloys whose composition is represented by the region in the diagram that lies to the left of the line A D.

Formation of Pearlite, or the Eutectoid: By studying the cooling of the primary austenite through the region below M P, it is found that this

solid solution of carbon in iron undergoes changes similar in character to those presented by the freezing of the liquid solution. These changes are represented by a secondary set of curves as shown in the part of the diagram to the left of A D. This diagram indicates that a substance corresponding to the eutectic of liquid alloys is formed and that it contains about .85 per cent. carbon, but since it is formed from a solid solution, it is called the **eutectoid,** a term that means "something of the nature of an eutectic." It will be observed that as the primary austenite is cooled from M P, the line of complete solidification, that any alloy with a carbon content greater than .85 per cent. precipitates iron carbide, Fe_3C, along the line P O′, whereas those in which the carbon content is less than .85 per cent. throw out of solution pure iron or ferrite along M′ O′ until the eutectoid composition is reached. The unchanged alloy, to which the term mother metal may be applied, then undergoes a change wherein the precipitation of both the iron and the iron carbide, Fe_3C, is completed simultaneously, with the result that the eutectoid thus formed consists of interstratified layers of ferrite and cementite, commonly called pearlite, as previously explained. Hence, the term eutectoid is often applied to pearlite, when it is desired to indicate the manner of its formation and its structural characteristics. Since the metal is in the solid form during these changes, it having reached its freezing point 500° to 800° C. above the temperature of formation for pearlite, the cause for these changes cannot be ascribed to a change in state. While many theories have been advanced to explain this and other facts the most satisfactory explanation is that iron exists in at least two, possibly three, allotropic forms. Thus, below a temperature of 690° C. it exists in a form designated as the alpha form, in which it has no power of dissolving carbon or the carbide, cementite, whereas above this temperature it can hold this constituent in solid solution. At these higher temperatures it is designated as the gamma form, and the solid solution of carbon in iron, is, metallographically, called **austenite.** Furthermore, the change from austenite to pearlite is not instantaneous, and, as will be explained later, several transition products may intervene, the complete series being austenite, martensite, troostite, sorbite and pearlite. From what has been said, it is evident that a steel that contains .85 per cent. carbon will, if cooled slowly from any point above the critical temperature for its formation, consist entirely of pearlite. Such steels are designated as **eutectoid steels,** while those that contain less than .85 per cent. carbon are termed **hypo-eutectoid steels,** and those in which the carbon content exceeds .85 per cent. are called **hyper-eutectoid steels.** Other phenomena which accompany the cooling of the primary austenite will be described in the next section.

Structural Constituents of Slowly Cooled Steel: All steels that have been cooled slowly from a temperature above that for the formation of pearlite will contain it as a constituent. Thus, in the case of hypo-eutectoid steels, all the carbon present will be found as pearlitic cementite,

the amount of pearlite being controlled by the amount of carbon present. Any ferrite above that required by the cementite in the formation of pearlite will be rejected as free, or excess, ferrite. In such steels, this excess ferrite is in the form of a network surrounding small masses of the pearlite. In the case of hyper-eutectoid steels, the amount of pearlite is again controlled by the carbon, but in an indirect way. As all the carbon combines with iron to form cementite, only a limited portion of ferrite remains for the formation of pearlite. As this ferrite is not sufficient to interstratify with all of the cementite, an excess of the latter remains. Like the rejected ferrite, this excess cementite will also appear as a network about the masses of pearlite. Thus, from the carbon content of a slowly cooled steel, it is possible to determine accurately the structural composition, or from the relative proportions of pearlite and ferrite or cementite as revealed by the microscope, the practiced metallographer can determine the approximate carbon content.

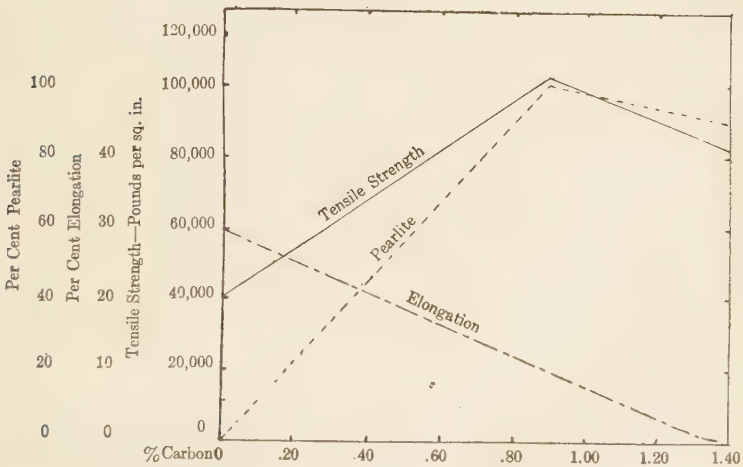


FIG. 196. Diagram Showing the Approximate Influence of Carbon Upon the Strength and Ductility of Steel and its Relation to the Pearlite Content.

Effect of These Constituents Upon the Physical Properties: The data on the physical properties of these constituents enable the student to understand the remarkable effect of carbon upon the physical properties of ordinary steel. In brief, the facts in their relation to the static strength of slowly cooled steel are as follows: 1. Each constituent has the power to impart to the steel its own properties in proportion to the extent of its presence. 2. Ferrite has the minimum tensile strength but maximum ductility. 3. Pearlite has maximum tensile strength with low ductility. 4. Cementite has great hardness and brittleness with more or less strength,

the value of which, as it occurs in steel, is difficult to determine. The effect of these constituents upon the properties of steel are plainly shown in the diagram, Fig. 196.

SECTION II.

THERMAL CRITICAL POINTS OF STEEL.

Nature of Critical Points or Ranges of Steel: The structural and other changes in steel just described take place at temperatures known as the thermal critical points, or critical ranges, because they are points in the cooling or heating of the metal that are marked by the spontaneous evolution or absorption of heat. The most marked of these is the range commonly called the point of **recalescence** and point of **decalescence.**

Thermal Critical Point for Eutectoid Steel: For example, suppose a piece of steel, containing .90 per cent. carbon and at a temperature of 1000° C. (1832° F.) be allowed to cool slowly. If, now, the rate of cooling be carefully ascertained by means of a pyrometer, it will be found that the cooling proceeds at first at a uniformly retarded rate, thus following the law for all cooling bodies. But when a temperature of about 700° C. (1292° F.) is reached, the uniformly retarded cooling is momentarily arrested. A pyrometer will not only fail to record any further decrease in temperature, but in most cases, when the conditions are favorable, will show that the temperature of the cooling mass actually rises. These facts show that heat is spontaneously generated within the metallic body in amount sufficient to balance, or more than balance, that lost through radiation and conduction. If the experiment is performed in the dark, the steel will be observed to glow at this point due to the heat evolved, and so the term recalescence has been applied to it. Investigation has shown that the amount of heat given off in this case is about 16 cal. per gram of pearlite.

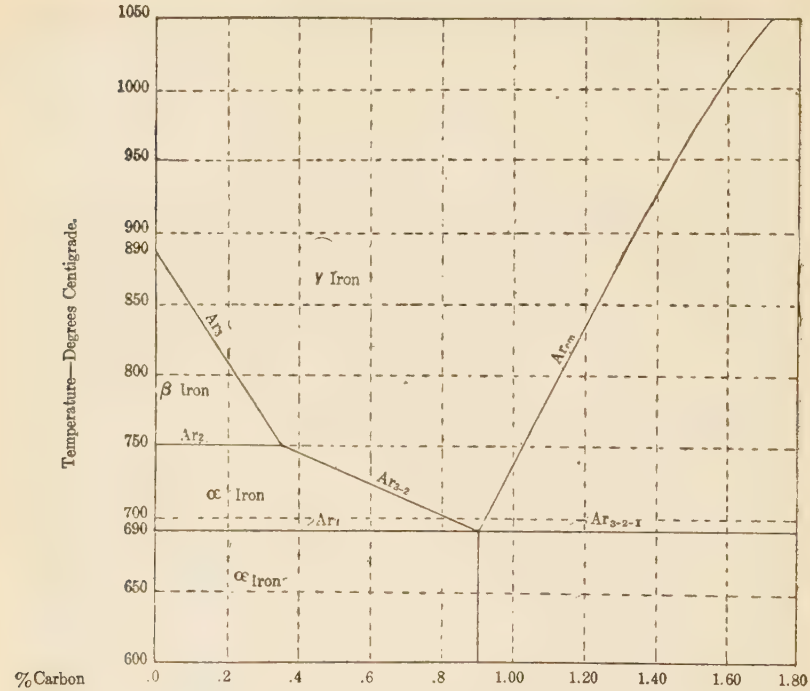
Thermal Critical Points for Pure Iron: If instead of the eutectoid steel, a piece of the purest iron obtainable be substituted in the experiment just described, the cooling of this pure iron is found to be very unlike that of the eutectoid steel. Thus, the metal will be found to cool at a uniformly retarded rate till a temperature of 900° C. (1652° F.) is reached, when a marked increase in retardation occurs, showing that heat is being evolved, but insufficient to cause an actual rise in temperature of the body of metal, i. e., a recalescence. The cooling will then resume a normal rate until the temperature of about 760° C. (1400° F.) is reached, when a second evolution of heat takes place, but not so pronounced as in the first instance. The metal then cools normally to atmospheric temperatures. Thus, in pure iron there are two evolutions of heat, i. e., two critical points, both of which take place at a higher temperature than that noted for eutectoid steel and without actual rise in temperature. Carbonless iron, therefore, has no point of recalescence.

Thermal Critical Points of Low Carbon Steel: If the same experiment be now performed with a steel containing even a small per cent. of carbon, say .10 per cent., the influence of this element is found to be very marked. Three thermal retardations will be detected, the first, the most marked, at about 850° C. (1562° F.), the second near 760° C., and the third at the point of recalescence, near 700° C. The last two are very faint.

Thermal Critical Points of Medium Carbon Steel: If the experiment with low carbon steels be repeated with specimens containing higher and higher percentages of carbon, the upper critical points observed in the preceding experiment on .10 per cent. carbon steel and carbonless iron will be found to be lower and lower as the percentage of carbon is increased, until, finally, the determination of the rate of cooling of a steel containing .35 per cent. or .40 per cent. carbon reveals only two critical points, the upper one at about 740° C. (1364° F.) and the other at the point of recalescence, 700° C. This fact means that the carbon has caused the two upper points observed in pure iron and low carbon steels to merge into one critical point. Furthermore, experiments on steel containing a higher per cent. of carbon than .40 show that the two lower critical points remaining also apparently merge into one on steels containing .60 per cent. carbon and over. Theoretically, this apparent merging should not take place till the steel is composed entirely of pearlite, that is, when it has the eutectoid composition and contains .85 per cent. to .90 per cent. carbon. The early merging is attributed to the difficulty of distinguishing by experiment two critical points so close together.

The Carbon-iron Diagram for Steels and Methods of Notation: These critical points or ranges are indicated graphically in the accompanying diagram of Fig. 197, which is seen to be the same as that used in explaining the formation of pearlite. This diagram refers to the critical points on cooling, which occur at temperatures somewhat lower than on heating. All these critical ranges are denoted by the letter "A," followed by either the small letter r, an abbreviation for the French word "refroidissement," cooling, or the small letter c, which stands for "chauffage," signifying heating. These signs, Ar and Ac, are further modified by the numerals 1, 2, 3, indicating the point of recalescence, the second, and the third points encountered on heating, respectively. Thus, Ac_1 means the first critical point passed upon heating the steel, and so on.

The Position of the Critical Ranges is affected in many ways. Attention has already been called to the difference between the ranges on heating and cooling. In commercially pure carbon steels, Ar_1 almost invariably takes place between 690° C. and 720° C. (1274° and 1328° F.) on slow cooling and Ac_1 20 to 40 degrees higher. It has been well established that this lagging of the point on cooling and the point on heating behind the true point is a case of hysteresis, often observed in physical phenomena. Evidence of the correctness of this explanation is found in the fact that the slower the heating and cooling the nearer the two points approach



%Carbon	.0	.2	.4	.6	.8	1.00	1.20	1.40	1.60	1.80
%Cementite	0.	3.	6.	9.	12.	15.	18.	21.	24.	27.
%Pearlite	0.	24.	48.	72.	96.	100. 97.+	94.—	90.+	87.—	83.+
%Free Ferrite	100.	76.	52.	28.	4.	0. 0.	0.	0.	0.	0.
%Free Cementite	0.	0.	0.	0.	0.	0. 3.	6.	10.	13.	17.

FIG. 197. Diagram Showing Position of the Critical Ranges in Slow Cooling and the Relation of the Carbon Content to that of Pearlite and Ferrite and Cementite.

each other. Also, if the cooling be exceedingly rapid, as in quenching with water, it is readily shown by magnetic and other simple tests that the Ar_1 point in some high carbon steels is lowered to 250° C. (482° F.) or under. The speed of cooling or heating, then, is the first factor affecting the position of these points. A second factor influencing the positions of Ar_1 is found in the temperature to which the steel is heated before cooling begins. The higher this temperature and the longer it is held at the high temperature the lower the position of Ar_1 will be; but this change in position of the critical point is not pronounced and takes place very gradually and slowly. A third factor is that of chemical composition. In general the presence of impurities in the steel have a tendency to lower the position of Ac and Ar, and in some cases this tendency is very decided. Thus, manganese lowers the position of Ar some 25° C. to 50° C. for each per cent. of that element present in the steel. Nickel and copper also lower the Ar range. In the case of nickel and manganese the lowering

is so pronounced that in a steel containing 13 per cent. Mn. or 25 per cent. Ni. no retardation is observed in cooling from a high to atmospheric temperature, but appears on cooling in liquid air, which indicates that the Ar_1 point has been lowered in these steels to below the temperature of the air. In the ordinary steel of commercial quality, the impurities are present in so small amounts that they can cause little variation in the position of the critical points.

Changes at the Thermal Critical Points: Besides the rise in temperature or retardation of cooling already explained, careful investigation has shown that other important changes take place in steels in passing through these ranges. For convenience these changes and their effects are summed up as follows:—

I. **Changes at A_3:** The point A_3, as already shown, applies to carbonless iron and steels containing less than .35 per cent. carbon. The passing of such steels through this point is accompanied by the following phenomena: 1. On cooling, the metal, which above Ar_3 was contracting, undergoes a sudden and marked expansion in volume on passing through Ar_3. In linear units the expansion amounts to about one-thousandth of its length. This dilation is then immediately followed by normal contraction, again. 2. Above A_3 the metal has an electrical resistance about ten times greater than its resistance at ordinary temperatures. At Ar_3 a sudden drop in this resistance takes place, after which the decrease proceeds slowly at a uniform rate until atmospheric temperature is reached. 3. A change in the crystallization of iron takes place at A_3. As explained in discussing the mechanical properties of steel, this change involves a rearrangement of the atoms within the grain. Below A_3 the pattern, or space lattice, after which the atoms are arranged is known as body-centered cubic, with one atom at each corner of the cube and one at the center, while above A_3 the pattern is described as face-centered cubic, with one atom at each corner and one atom at the center of each face. These patterns revealed by the X-ray correspond, respectively, to the two allotropic forms of iron known as alpha and gamma iron. 4. The tensile strength of iron at the A_3 point has been shown to undergo a distinct discontinuity, (see page 453). 5. The dissolving power of iron for carbon is one of the most important changes which the properties of the metal undergo in passing the Ac_3 point. From what has been said in the preceding section it may be surmised that below this point, or at least as long as the iron is in the alpha form, it has little, if any, power of dissolving carbon, but it gains this power immediately the Ac_3 point has been passed. 6. An abrupt structural change accompanies the passage of all low carbon steels through this range. It is on reaching this point that the excess ferrite begins to be set free, which continues till the residual austenite is of the proper composition for the formation of pearlite.

II. **Changes at A_2:** As indicated in the iron-carbon diagram, A_2 occurs as a separate point only in carbonless iron and in steels containing

less than .35 per cent. carbon. Just as the retardation on cooling was found to be faint at this point, so the changes in properties are not so numerous nor so marked as at A_3. Thus, there is no dilation, no structural change, no change in crystalline form, and probably no change in the dissolving power of iron for carbon on passing through the range A_2. But the following three changes in properties on passing A_2 are to be noted. The magnetic properties undergo a marked change on passing A_2. Above this point steel is non-magnetic, or para magnetic, but in passing through Ar_2 it suddenly becomes strongly magnetic, and gradually becomes more so as the cooling continues, finally gaining its full magnetism at a temperature of about 500° C. A distinct discontinuity in both the tensile strength and specific heat of iron at the A_2 point has been shown to take place.

III. **Changes at $A_{3,2}$**, which point results from the merging of A_3 and A_2, after a carbon content of .35 per cent. is exceeded, are the same as those occurring in low carbon steels in passing through A_3.

IV. **Changes at A_1:** As previously explained, the point A_1 occurs in all steels containing from a mere trace to .90 per cent. carbon. It corresponds to the transformation of residual austenite into pearlite. At this point the following sudden changes in properties are noted: 1. A dilatation takes place which increases with the carbon content, reaching a maximum with .85 per cent. carbon. 2. Increased magnetism takes place for all steels on cooling through this point. 3. A marked decrease in electrical resistance is also noted on cooling through this range. 4. Below this point iron loses entirely its power to dissolve carbon. 5. The important changes from austenite to pearlite have already been shown to take place at A_1, but it is well to emphasize their significance here, for these changes give the key to the rational treatment of steel. The spontaneous transformation of austenite of eutectoid composition into pearlite, that is, a solid solution into an aggregate, or vice versa, makes possible the refining of steel by heat treatment, because on being heated through its critical range, the steel is changed from a coarse aggregate to a fine, almost amorphous, solid solution. This fact is also the secret of hardening steel, as will be shown later.

Cause of the Thermal Critical Points in Iron: In seeking a cause for the existence of the thermal critical points in steel, all the phenomena exhibited must be considered. Starting first, then, with the thermal changes noted in the experiments previously described, it is well to note that there are but three well known causes of spontaneous evolution of heat in cooling bodies and of similar absorptions of heat on heating them. Briefly, these causes are (1.) the formation or decomposition of chemical compounds; (2.) changes of state, whether by solution or by the agency of heat; and (3.) allotropic or polymorphic transformations, which are always accompanied by either an absorption or evolution of heat when

the substance of the body passes from one allotropic condition to another. As to the upper points, A_3 and A_2, it has been shown that at these points even carbonless iron either absorbs or evolves heat, depending upon whether the metal is being heated or cooled while passing through the ranges. The fact that the iron is pure, nothing being present with which it could combine, and the fact that it is in the solid state throughout the experiment, preclude the possibility of either a chemical change or a change of state having taken place to cause the thermal changes indicated. Only the explanation founded on the basis of allotropy, therefore, remains.

Allotropic Forms of Iron: According to the two thermal changes that occur, then, pure iron or ferrite exists in at least three allotropic forms. Below the point A_2 it is called **alpha iron,** between A_2 and A_3 it is known as **beta iron,** while above A_3 it is said to be in the **gamma form.** However, in spite of the changes in physical properties exhibited by pure iron at 760—768° C., many authorities doubt the existence of the allotrope known as beta iron, and they cite good reasons to support their opinions. One thing that might cause some to doubt its existence is the fact that the presence of carbon seems to have no effect in lowering the point until the carbon content reaches .35 per cent., when it merges with A_3 and disappears altogether. But this lack of effect may be due to the fact that beta iron, like alpha iron, does not dissolve carbon. Again, since the influence of carbon is to delay the separation of ferrite, it may be that beta iron is not formed on cooling steels containing .35 per cent. carbon or more, for since the temperature of the point $Ar_{3\text{-}2}$ in such steels is below that for the formation of beta iron, it is probable that just as iodine passes directly from the solid to the gaseous state by sublimation, or as amorphous sulphur at atmospheric temperatures passes to rhombic sulphur, so gamma iron passes directly to the alpha form. The strongest evidence against its existence lies in the fact that, unlike gamma iron, beta iron has not only the same crystalline form as alpha iron, but, as determined by X-ray analysis,—exactly the same space lattice. This evidence will be hard to refute without modifying the definition for allotropy so as to exclude crystalline form and structure. At present, allotropy is defined as the power or ability exhibited by some chemical elements of changing or modifying their properties under different conditions without losing entirely their chemical identity. A better definition will be possible when the fundamental cause of allotropy, itself, has been discovered, and until that time beta iron may or may not be considered an allotrope of iron. As to gamma iron, all authorities agree that it is an allotrope. As already explained, the change in properties between alpha and gamma iron is very pronounced, and it is, furthermore, accompanied by a change in the arrangement of the atoms to form the grain or crystal, alpha iron being characterized by the body-centered cubic space lattice and gamma iron by a face-centered cubic space lattice.

Causes of the Thermal Critical Points in Steel: While the two preceding paragraphs give reasons for the A_3 and A_2 points in steel, as they appear in the light of present knowledge, other reasons must be found to account for the A_1 point. The fact that the point A_1 does not occur in carbonless iron and only faintly in low carbon steels, while with increase of the carbon it increases in intensity, is evidence that this point is due solely to the presence of carbon. Unlike the points A_3 and A_2, which are due to allotropic forms of iron, A_1 is not due to any change in the carbon itself, but to the formation of pearlite, which implies the crystallization, and probably the formation, of cementite, Fe_3C, coupled with the complete change of the ferrite from the gamma to the alpha state as well. Above A_1, the Fe_3C, or more probably the carbon, being in solution with the gamma iron and thoroughly diffused, has the power of imparting its own properties, hardness and brittleness, to the steel in a more pronounced way than when in the segregated form in which it occurs below A_1. Hence, formerly due to the theories then advanced to explain the hardening effect of carbon, the term **hardening carbon** was applied to it above A_1, while below A_1 it was called **cement carbon.**

SECTION III.

THE CRYSTALLINE STRUCTURE OF STEEL.

Crystals and Grains: That the crystalline structure of steel exerts a deep influence upon its strength and ductility is a well known fact. Since this structure lends itself to refinement through proper heat treatment, a clear understanding of all the laws governing the crystallization of steel is essential to the art of heat treating steel. When steel, like many other substances, passes from the liquid to the solid state, the process of solidification is accompanied by crystallization, that is, the atoms, or molecules, of the various ingredients arrange themselves so as to form small bodies having regular geometrical outlines. Each of such bodies constitutes a crystal. As was stated at the beginning of Part II of this book (See page 417), crystals have the remarkable property of breaking most easily along certain planes usually parallel to the faces of the crystal. In the case of brittle crystals, these planes of easy rupture are called **cleavage planes,** but in the case of ductile crystals they are called **slip planes.** The direction of the cleavage planes, or slip planes, constitutes the **orientation** of the crystal. Perfect crystals, called **idiomorphic crystals,** are formed only when the conditions are favorable. Thus, with high fluidity, absence of foreign particles, slow rate of cooling, and with the liquid at rest and undisturbed, perfect crystals of large size may form.

Because of the unfavorable conditions that usually prevail in its manufacture, the crystallization of steel results in the formation of imperfect crystals with irregular forms and smaller in size than perfect crystals. These imperfect crystals are, scientifically, designated as **allotrimorphic crystals,** but the metallurgist speaks of them simply as **grains.** These grains retain all the other characteristics of crystals.

Crystallization of Steel: As an aid to understanding the crystallization of steel it will, perhaps, be best to follow the crystallographic history of a steel casting that is allowed to cool slowly from the casting temperature to atmospheric temperature. For the present, let this steel be of any carbon content. During the solidification period, what has been termed the primary crystallization takes place, which consists in the formation of macroscopic tree-like bodies of austenite called dendrites. Each of these dendrites is composed of very small bodies, each having a form which is representative of the crystallographic form for austenite. Of these, Stead writes: "The fine fir-tree crystallites, containing probably a fraction of the amount of the carbon in the liquid steel, grow steadily forward from the cold surface of the containing moulds. The crystallites develop branches in three directions corresponding to the axes of the cube, and these branches throw out similar branches themselves. Eventually parts of the most fusible portions are trapped between the branches and are the last to solidify. When there is much phosphorus or some sulphur in the metal, they are always present together with an excess of the carbon in the last residue of metal that remains liquid, and although in cooling down, after the liquid has solidified, the excess carbon diffuses out of it into the purer part, the sulphides and phosphides do not, but remain fixed, and can generally be detected in the solid metal."

While solidification is taking place, or immediately following the formation of the dendrites, a crystalline transformation, called granulation, sets in and continues until the critical range is reached, where all steels are found to be made up of grains, each grain having its own orientation, which results from the block-like structure built up by the regular arrangement of the atoms. The process involves grain growth, so the size of these grains varies with the rate of cooling. In passing through the critical range the structural changes are affected by the amount of carbon present, and for this reason it is best to consider the three grades of eutectoid, hypo-eutectoid, and hyper-eutectoid steels separately from this point onward.

Crystallization of Eutectoid Steels: In the eutectoid steels the growth of the grains will continue down to the point Ar_1, where the metal will be made up of grains of austenite containing ferrite and cementite in proper proportions to form pearlite. Therefore, in passing through the critical point, Ar_1, each austenite grain, if the cooling is slow, apparently

changes bodily into a grain of pearlite. If the cooling is rapid, structures intermediate between austenite and pearlite will be formed, for the complete change requires a certain amount of time. Hence, a coarse austenitic structure acquired by cooling slowly from a high temperature gives rise to a correspondingly coarse pearlite structure.

Crystallization of Hypo-Eutectoid Steel: As an example of the genesis of the crystalline structure of steels of hypo-eutectoid composition, let a steel containing .60 per cent. carbon, corresponding to 72 per cent. pearlite and 28 per cent. free ferrite, be selected. In such a steel the granulation will proceed till the upper critical point Ar_{3-2} is reached, where free ferrite begins to be rejected and continues till the point Ar_1 is reached, when the residual austenite, being of the proper eutectoid composition, passes into pearlite as described for eutectoid steels. An important point to be noted here is the fact that this setting free of the excess ferrite is brought about through the rejection of ferrite in excess of the eutectoid composition **by each individual grain of austenite,** either to its boundaries or between its cleavage planes. When each grain of austenite becomes a grain of pearlite, the ferrite previously rejected still remains as an envelope, thus forming the net-work mentioned under "Ferrite." Therefore, the structure of cast hypo-eutectoid steel is apt to be very coarse, for the following three reasons: 1. The slow and undisturbed cooling promotes the formation of large austenite grains and hence, later, of large pearlite grains. 2. The slow cooling between the upper and lower critical points favors the rejection of a maximum amount of free ferrite, which rejection makes for coarseness of structure. 3. The slow cooling from the upper critical point to atmospheric temperature promotes the crystallization of excess ferrite into large grains, especially when this excess is large in amount, i. e., in very low carbon steel. Because of its coarse structure, cast hypo-eutectoid steel is less tenacious and frequently less ductile than forged, rolled or properly annealed steel of similar composition.

Crystallization of Hyper-Eutectoid Steels: In the case of hyper-eutectoid steels, the granulation proceeds to the point Acm, a temperature that is indicated by the line Acm in Fig. 197, where excess cementite is liberated—like the excess ferrite in hypo-eutectoid steels. This excess cementite is rejected either to the boundaries of the austenite grains or between their cleavage planes, where, after the transformation of eutectoid austenite into pearlite, it remains to form a network about the grains of the latter.

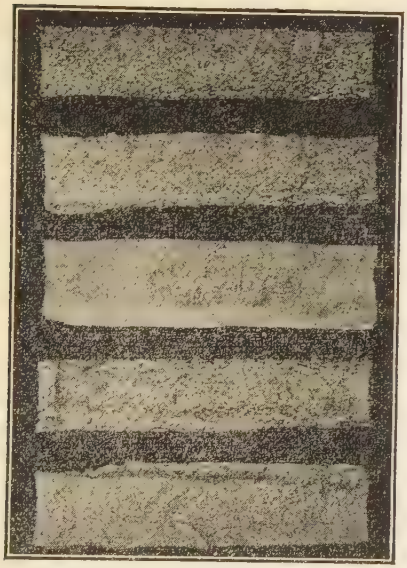
The Effect of Work on Grain Size: The effect of work on the mechanical properties of steel has been discussed in the second part of this book. There it was also pointed out that some of the benefits of working as the steel cools to Ar_1 are due to a refinement in the grain size. The ex-

planation for this refinement is found in the fact that, as each grain is distorted by the application of mechanical pressure, it breaks up into a number of smaller grains possessing the characteristics of the original grain. An explanation of this phenomenon in the light of present knowledge is partly guesswork, but such a hypothesis may be useful in fixing the conditions and results of hot working in mind, which are of great practical importance. Let it be assumed that the steel is to be worked from a temperature of 1100° C., and that a grain of the austenite has just been distorted by pressure in a press, a blow from a hammer, or a pass through the rolls. It has already been stated that the distortion takes place by a kind of block movement, causing slippage along certain planes extending through the crystal. This movement tends to separate the crystal into fragments in which some of the atoms maintain their original positions relative to each other, but the atoms adjacent to the slip planes become more or less disorganized and the forces of attraction and vibration are in metastable equilibrium. However, as the vibratory motion of the atoms is great, these disorganized atoms are capable of quickly rearranging themselves. Each fragment, or undisorganized part of the original crystal, therefore, becomes a center for crystalline growth. This growth takes place rapidly while equilibrium is being established among the disorganized atoms, then more slowly until stable equilibrium is established among all the grains as well. Equilibrium among the grains depends on the temperature, hence, if the temperature were kept constant, the new grains would grow to the size of the original grains. But the piece is cooling in the meantime, which retards the grain growth, and before the grains reach the size of the parent grains, they are likely, in any process of continuous working, to be distorted again by a second blow or application of pressure, which would break them up as before. Thus, it is clear that working above the critical range, Ac_3, gives no permanent distortion of the grains, and that, starting at a given temperature, the size of the grains will depend upon the temperature above the critical at which the working is completed and the amount of work done within this working range. If the steel be worked at temperatures below Ar_1, and the annealing point, no refinement of grain takes place, as the great rigidity of the metal or its lack of molecular energy prevents any readjustment of the grains at all. Hence, cold worked steel will show a pronounced distortion of grain.

Crystalline Changes on Heating Steel: Since the preceding discussions have been concerned mainly with steel under conditions of cooling, it may be profitable to review these changes from the standpoint of heating. Starting, then, with a low carbon steel, containing, say, .20 per cent. carbon, it will be found that, under normal conditions of manufacture and in its natural state, this steel consists of approximately 24 per cent. pearlite and 76 per cent. free alpha ferrite, the pearlite existing in small grains surrounded by the ferrite as a network. Upon heating through

the point Ac_1, the pearlite changes into austenite, the iron of which is in the gamma form; but the free ferrite is still in the alpha form. As the heating continues throughout the zone bounded by Ac_1 and Ac_2 the austenite thus formed begins to absorb the free ferrite. Upon passing through the Ac_2 range the remaining alpha ferrite changes into beta ferrite; and the steel as a whole will be found to be hard and non-magnetic. As the heating progresses through the second zone, lying between Ac_2 and Ac_3, the beta ferrite, which is only a remnant of the original alpha ferrite, is gradually absorbed, so that as the range Ac_3 is passed the whole of the steel passes into the condition of austentite, or a solution of carbon in gamma iron. In a similar manner the changes in the constituents of steels of any carbon content up to eutectoid steel might be explained. In each case, however, it is to be noted that the temperature at which the transformations are completed falls as the carbon content is increased, being at its lowest when the eutectoid ratio has been reached. In the case of hyper-eutectoid steels, the free cementite is absorbed in a manner analogous to the absorption of free ferrite in hypo-eutectoid steels. But the final solution of the cementite takes place at a temperature range indicated by the area between the lines A_1 and Acm (Fig. 197), and much more slowly than ferrite. This latter point, being a matter of great practical importance, should be kept in mind.

Crystalline Refinement on Heating: Besides these changes in structural constituents brought about by heating the steel through the various critical ranges, there still remains a matter of extreme importance to be explained. This matter refers to the crystalline, or grain, refinement observed when a steel is heated through these ranges. Again assuming that the steel is in a normal condition after manufacture in the usual manner, no change on heating is observed to take place in the grain structure until the temperature has reached that of the lower critical range, Ac_1. At this temperature, which marks the point where the original pearlite grains are transformed into austenite grains, the maximum refinement, that is, the smallest grain size possible, occurs. This refinement is to be expected from the conditions of the formation of the austenite. It will be recalled that the formation of austenite under these conditions requires a change in the iron from the alpha to the gamma form, or a rearrangement of the atoms from the body-centered cubic space lattice to the face-centered cubic space lattice, and in all probability a decomposition of the cementite and absorption of carbon by atomic dispersion. Thus, a complete disorganization of the structural constituents of the steel must result in every part of it at some stage of the transformation, and since this disorganization occurs at the lowest temperature for the formation of austenite, conditions are most unfavorable for rapid grain growth. Hence, the austenite is found to be almost amorphous in respect to its grain structure. But it is to be especially noted that grain growth begins as soon as the temperature is raised above this critical range, which fact



1. Heated to about 1300° C. and quenched in water.

2. Heated considerably above the critical range and quenched in water.

3. Heated to just above the critical range and quenched in water.

4. Heated to just below the critical range and quenched in water.

5. Steel as forged and cooled in air to atmospheric temperatures.

FIG. 198. Natural Size Photographs Showing Effect of Heat Upon Grain Size of a Rolled and Forged Steel, Carbon .75% (Metcalf's Experiment).

1. Steel as cast and cooled naturally.

2. Heated to 927° C. and quenched in water.

FIG. 199. Natural Size Photographs Showing Effect of Heat Upon the Grain Size of Cast Steel. Specimens, left to right, contain, .25% Carbon and .36% Carbon.

results in a gradual coarsening of the grain of the austenite as the temperature is progressively raised above this range. It is also to be noted that this increase in grain size not only varies with the temperature above the critical range, but also with the length of time at which the steel is maintained at the high temperature. In eutectoid steels, then, complete and maximum refinement of the grain takes place immediately the point Ac_1 is passed. But if the steel contains free ferrite or free cementite, that is, if it is of hypo-eutectoid or hyper-eutectoid grade, then the steel as a whole is not refined on passing Ac_1, because the excess ferrite or cementite remains unaltered. In all cases it is only when all the constituents of the steel have passed into the state of a solid solution, or austenite, that complete refinement can be obtained. To bring about such a condition, it is necessary to heat such steels to a temperature a little above that of their upper critical points as indicated on the iron carbon diagram, on account of hysteresis previously discussed.

Practical Importance of Grain Structure: That the proper refinement of grain structure is of great practical importance is evident from what has already been said. Another illustration of the ways in which the facts pointed out above in connection with the effects of mechanical work and heat upon the grain structure of steel may be practically applied is furnished by the welding of steel. If two steel bars are welded together by scarfing the ends slightly and hammering lightly over the weld only, as is the practice of most blacksmiths in welding iron bars, it is found that, while the weld itself is strong, the welded bar will be weak on each side of the weld. A bending test applied to such a weld generally causes the bar to break a short distance from the weld, which fact is responsible for the assertion, often made by some blacksmiths, that the weld is stronger than the bar. A careful examination of the whole bar, however, will usually show that the regions on each side of the weld are the weakest points in the entire bar. Evidently this weakness has been developed in the process of welding. The high temperature required in welding increases the grain size of the ends to be welded for a considerable distance along the bars. The subsequent hammering refines this large grain in the weld itself, but not in the areas on each side of it. By changing the manner of welding somewhat, the structure of the welded bar can be made almost uniform throughout, and these defective areas will not appear. This result can be accomplished by making the weld in the following manner, which is the usual practice in welding steel: The two ends to be welded are first heated to a moderate forging temperature for a distance of several inches back, the exact distance depending upon the size of the bar; these ends are then stove up, or upset, that is, the heated regions are shortened and thickened by hammering directly against the ends. Next, the ends are scarfed, but instead of a short, blunt scarf sometimes used, a well beveled scarf should be made. The scarfed ends are then heated to a welding temperature; a flux of common river sand or a reliable

commercial welding compound is applied; the weld is made as usual; and the thickened portion of the bar is forged down to a size conforming to the remainder. This forging refines the grain which had previously been made coarse by the heating, and makes the structure of the bar more nearly uniform. If the bars have been stove up right in the beginning, the form of the weld will be such as to require the greatest amount of forging where the grain is the largest and will decrease to none where the steel was heated only to the critical range. Similarly, electric and oxy-acetylene, or other forms of autogenous welding are apt to change the structure of the steel in the immediate vicinity of the weld, and since no mechanical work is done, the grain size can be controlled only through temperature and rate of cooling.

Summary of Chapter I.: The conditions and properties of the iron-carbon alloys and their constituents may be summed up about as follows: Above the critical ranges, the iron is in the gamma form, and the carbon is dissolved, thus imparting to the alloy, when the carbon is present to the amount of about .30 per cent., the power of hardening materially by ordinary method of rapid cooling; the alloys are non-magnetic and in a crystalline form; and the grains grow on heating and cooling slowly, but mechanical working prevents the growth of the crystals and reduces their size. Below the critical range, the metal represents an aggregate of ferrite and cementite, Fe_3C, and it possesses little hardening power. Here the iron is in the alpha form, the alloys are magnetic, no crystallization takes place, and mechanical working distorts the grain structure.

CHAPTER II.

HEAT TREATING THEORY AND PRACTICE.

Introduction: While considerable time has now been spent in a discussion of subjects that may appear to be purely theoretical in nature and of little practical value, yet this course is justified, because the principles explained form the basis of all heat treating processes, and a clear understanding of them is therefore essential. The practical application of these principles will now be considered under the following headings, corresponding to the three chief processes of heat treatment as stated in the introductory paragraph to Part III.

SECTION I.

ANNEALING.

The Annealing Operation consists in (1) heating the steel to some predetermined temperature, (2) keeping the temperature constant at the predetermined point for a given length of time, and (3) cooling the steel according to some predetermined course to atmospheric temperature. To accomplish the desired result in the given steel to be treated requires that all three of these steps in the annealing operation be very carefully planned and as carefully carried out, for the success of the operation depends entirely upon the proper correlation of the rate of heating, the temperature to which the steel is heated, the time it is kept at the annealing temperature and the rate of cooling.

Purpose of Annealing: Evidently, then, the annealing operation will be modified to suit the end sought. In general, the purpose of annealing may involve any one or all of the following aims: 1. To soften the steel in order that it may meet certain physical requirements or be more easily machined. 2. To relieve internal stresses and strains induced by forging, rolling, or drawing, or by a non-uniform contraction in cooling. 3. To remove coarseness of grain and thus secure a more desirable combination of strength, elasticity and ductility for resisting the stresses to which it is to be subjected in service. The treatment is generally applied (1) to hot forged steel objects, because their grain structure is generally more or less heterogeneous and, owing to high finishing temperature, relatively coarse; (2) to cold worked steel, such as sheets and cold drawn wire, which often must be annealed in order to increase or restore its ductility; and (3) to steel castings, which usually have so coarse a grain structure as to be very deficient both in strength and ductility.

True Annealing and "Process" or "Works" Annealing: To accomplish the results sought as expressed above in aims (1) and (2), it is not always necessary to heat the steel to the critical range. Thus, in the "process" or "works" annealing employed in wire drawing, it is only necessary after cold working to heat the steel, which contains less than .30 per cent. carbon, to about 600° C. in order to relieve the strained condition of the ferrite and restore the ductility. The same statement also applies in the case of the "white annealing" of cold rolled sheets. It is to be noted, however, that this treatment does not develop the maximum softness, because the pearlite is not affected unless the steel is held for a long time at a temperature slightly higher than 600° C. But as this constituent is present in so small amounts, its influence is scarcely evident. If higher carbon steels are held at about 700° C. for a sufficiently long period, the stratified structure of the pearlite is destroyed, and the ferrite and cementite coalese. This method is often applied to tool steels in order to soften them for machining. All true or full annealing, however, requires that the steel be heated to a temperature above that of its upper critical range, and it is to this true annealing the following discussion is to be confined.

Heating for True Annealing: The first step in the annealing operation is to heat the steel past its critical range, for in so doing the previous structure is completely obliterated and a new one, nearly amorphous, is born. As has been previously explained, this important change is due to the passage of the steel structure from the state of an aggregate of ferrite and cementite to a homogeneous solid solution. Should the steel remain below the critical range, no structural change takes place, if the case of strain relief noted above in cold worked steel be excepted. The coarsening effect upon the grain size of steel, brought about by heating above this range, has already been explained. The proper temperature, then, for true annealing is one but slightly above the critical range of the steel, and this temperature must be maintained uniformly as near the range as possible during the time the steel remains at the annealing temperature.

The following ranges of temperatures are recommended by the committee on heat treatment of the American Society for Testing Materials.

TABLE 67. Annealing Temperatures as Recommended by the American Society for Testing Materials.

Range of Carbon Content.	Range of Annealing Temperature.
Less than 0.12 per cent.	875 to 925 degrees C.
0.12 to 0.25 per cent.	840 to 870 degrees C.
0.30 to 0.49 per cent.	815 to 840 degrees C.
0.50 to 1.00 per cent.	790 to 815 degrees C.

These temperatures are shown diagramatically in the accompanying figure, together with recommendations by other authorities.

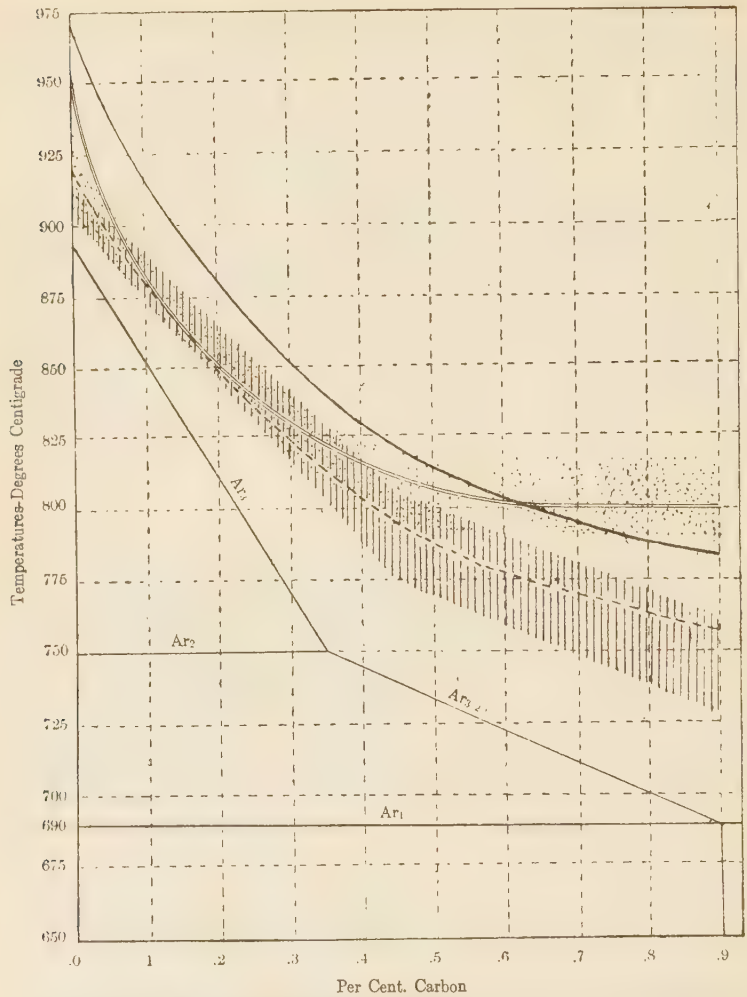


FIG. 200. Annealing (and Hardening) Ranges Showing Approximately the Temperatures Recommended by Different Authorities.

Legend.

..... Sauveur (for treating forgings).
..... American Society for Testing Materials.
..... Bullens (for annealing and hardening).
Stead's Lower Curve (for refining and hardening).
Stead's Upper Curve (for annealing and normalizing).

In large bodies, the central portion will lag in temperature behind the exterior, hence such objects should be heated very slowly, for very evident reasons. The practice of raising the temperature of the furnace beyond the proper annealing temperature in order to drive the heat to the interior of the piece is a great mistake, for then the temperature of the exterior may be carried beyond the proper point with consequent evil results attending.

Importance of Time in Heating for Annealing: The time the object should remain at the annealing temperature is governed largely by its size. Evidently, it should be maintained at this temperature until it has become uniformly heated throughout. The committee quoted above recommends that an exposure of one hour is sufficient for pieces twelve inches thick. In practice, however, it is often necessary to keep the object at the annealing temperature for a much longer period than that indicated by the committee or that which theoretically would appear sufficient. This is especially true with plain steel in cases where the mechanical work upon the steel has been severe, or where the steel has been improperly heated in working, and in certain of the alloy steels. It has been shown by Bullens[1] "that the greater the internal stress upon the steel the greater is the amount of lag, or final release, of this stress behind the actual change of constituents. That is, even though a totally new structure may be formed by the annealing temperature, there remains for a considerable length of time a tendency of the new structure to return, upon slow cooling, to the stressed condition of the original, even though the constituents themselves may be those born at the new temperature. It is important, therefore, if a soft steel free from all internal stresses and strains is desired, that a sufficient length of time be allowed for the permanent elimination of these stresses and strains, before cooling." To accomplish this result a period of time extending over several hours, or even days, may be required.

Cooling: Having, thus, by proper rate of heating and length of time of heating, obtained the steel in a state favorable to maximum refinement, the next step is to cool it properly. As variations in the rate of cooling produce very profound effects upon the physical properties of the metal, this process is not as simple as it appears. The effects of cooling at different rates and in different ways should, then, be carefully studied. The property most noticeably affected by the cooling process is the hardness. As is well known, this property in a given steel depends upon the rate of cooling from above the critical range. Thus, by the most rapid cooling, it is possible to develop the maximum hardness, or by the slowest cooling the greatest softness, and by varying the rate of cooling any degree of hardness between these extremes may be obtained. In searching for a reason for these changes in properties, it is not surprising that investigators have found that important structural changes accompany all cooling, and that these changes vary, in the effects they produce, with the speed of the cooling.

[1]Steel and Its Heat Treatment, Second Edition, pp. 133 to 148.

Effect of Cooling on the Net Work: The first of these structural changes that may be mentioned is the effect of different rates of slow cooling upon the net work of ferrite described in the preceding section of this book. Thus, in very slow cooling of hypo-eutectoid steels from the annealing temperature a coalescence of the excess ferrite into large grains intermingling with coarse pearlite grains results. If the steel be now cooled rather rapidly, but still not so rapidly as to prevent the formation of pearlite, the excess ferrite will be found to be of a fine grain structure and to form a fine net work about the pearlite. If, now, these two methods be combined, that is, if the cooling be made to proceed rapidly through the upper part of the transformation range then slowly to atmospheric temperature, the net work of ferrite is fine, but the pearlite is better developed than in the second case.

The Effect of Cooling Upon Pearlite now remains to be explained. While the rate of cooling from below the critical range can have no effect upon the pearlite, changing the rate of cooling while the steel is passing through this range and the solid solution is being transformed into pearlite will correspondingly change the arrangement of the ferrite and cementite composing the pearlite, so that the same steel may be made to exhibit widely differing physical properties. As mentioned before, the austenite does not pass directly into the pearlitic condition on cooling through the critical range, but makes the change by way of the three transition stages known as martensite, troostite, and sorbite. Of these, only sorbite is retained in the steel by annealing methods of cooling. In small sections it is retained by air cooling through the lower critical range. By varying the cooling through this range this change from sorbite to pearlite may be controlled so as to produce five phases, or varieties, of pearlite having different physical properties as follows:—

1st Phase. True Sorbite with emulsified Fe_3C. Very dark on etching. Tensile strength, 150,000. Elongation, 10% in two inches.

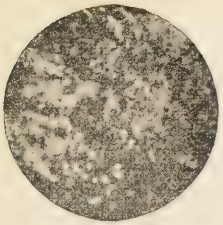
2d Phase. Sorbitic pearlite with semi segregated Fe_3C. Dark on etching. Tensile strength, 125,000. Elongation, 15% in two inches.

3d Phase. Finely laminated pearlite with Fe_3C almost completely segregated. Exhibits a play of gorgeous colours when lightly etched. Tensile strength, 100,000. Elongation, 10% in two inches.

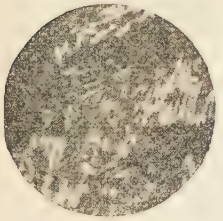
4th Phase. Fully laminated pearlite with completely segregated Fe_3C. Tensile strength, 85,000. Elongation, 8% in two inches.

5th Phase. Massive pearlite, consisting of coagulated Fe_3C and ferrite. Tensile strength, 75,000. Elongation, 5% in two inches.

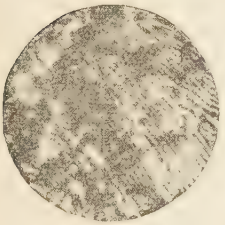
The second phase is the one sought in the process of patenting in wire drawing. So, it is seen that, having obtained the greatest possible refinement as to grain size and released all the internal stresses and strains in the metal by heating to the proper temperature, it still remains to adjust the physical properties by regulating the rate and the manner of cooling.



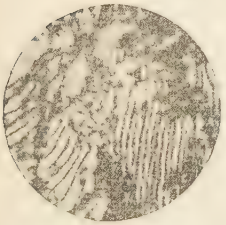
1. Sorbite. Cementite is emulsified. Obtained in steels of low carbon content by cooling rapidly to atmospheric temperatures. In medium and high carbon steels it is obtained by cooling rapidly through the critical range only, or reheating to about 600° C. after cooling rapidly.



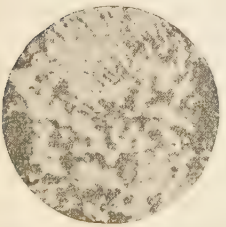
2. Sorbitic Pearlite. Cementite is partly segregated. Obtained by cooling rapidly through the upper range only.



3. Normal Pearlite. Cementite is largely segregated. Obtained by moderately slow cooling.



4. Laminated Pearlite. Cementite is completely segregated. Obtained by slow cooling.



5. Massive Pearlite. Cementite and ferrite are coagulated. Obtained by very slow cooling to atmospheric temperatures.

FIG. 201. Microphotographs Showing Progressive Segregation of Cementite in the Development of Pearlite from Sorbite. (White areas represent ferrite, black areas, cementite.)

Other Factors to consider in cooling are the carbon content and the size of the object. In general, the lower the carbon the more rapid may be the rate of cooling without affecting to any marked degree the softness and ductility of the metal. For example, steels containing less than .15 per cent. carbon may even be quenched in water, and those containing less than .30 per cent. carbon, in oil, without markedly decreasing their ductility. The effect of quenching will depend on the size of the section, the effects being more marked in small than in large sections. In order to secure the same rate of cooling in objects of different size, it is obviously necessary to regulate the external conditions in accordance with the dimensions of the objects treated. Thus, the cooling in air of a very fine wire may be equivalent to quenching in oil or water an axle of the same carbon content.

Methods of Cooling: In general, there are three methods of cooling, namely, furnace cooling, insulated cooling and air cooling. Of these, furnace cooling may be made the slowest, especially if the furnace is large and can be effectually sealed from air draughts. This method gives maximum softness and ductility. In other words, the tensile strength and elastic limit will be at their lowest, while the elongation and reduction in area will be at or near their maxima. Steel subjected to such treatment will resist severe distortions. In what has been termed above as insulated cooling, the object is removed from the furnace and covered with a blanket of lime, sand, ashes, etc., or it may be placed in a brick or concrete lined underground pit with a tight fitting cover, which in turn may be covered with ashes or loose earth. In cases where large amounts of steel are placed in a single pit, this method may be slower even than furnace cooling. In air cooling, the object is simply removed from the furnace and allowed to cool in the air. Evidently, the rate of cooling by this method will be affected by the size of the piece and the season of the year. In addition the physical properties imparted will depend somewhat upon the carbon content. Hence, the American Society for Testing Materials recommends that "Thick objects with less than 0.50 per cent. of carbon may be cooled completely in air, of course, protected from rain or snow. Objects with 0.50 per cent. of carbon or more, and thin objects with from 0.30 per cent. to 0.50 per cent. of carbon, may be cooled in air if their cooling is somewhat retarded, as for instance, by massing them together, as happens in the case of rails." The effect of the more rapid cooling in air is to increase the strength and elastic limit, but lower the reduction and elongation. In order to hasten the cooling, articles of low carbon content are sometimes immersed in water after they have become black in color. This method is then called water annealing.

Combination Methods of Cooling: Besides the three general methods of cooling described above, various combination methods have been employed with great success in cases where it is desirable to regulate

the mechanical properties closely. Three of these, as directed by Bullens, are as follows:

1. "Heat to slightly over Ac_3, air cool to just over Ar_1, return to a furnace which is held at that temperature (about 725 °C.), heat until uniform, and then cool slowly. The latter heating should not be any longer than is possible. This method will tend to prevent the formation of large amounts of free ferrite, but will affect the pearlite, as there will be slow cooling through the Ar_1 range. 2. Heat to slightly over the Ac_3 range, air cool to just under the Ar_1 range, return to a furnace and heat to 730° C. and slow cool. This method will effect a greater toughening, if the temperature has not been prolonged too greatly at the second heating. 3. Heat to slightly above Ac_3 air cool to below Ar_1, return to a furnace heated at a temperature slightly below Ar_1 (660° to 670° C.), hold at this temperature until uniformly heated, and slow cool (in lime or air). By permitting the steel to air cool to a temperature below the lowest transformation, advantage is taken of any 'hardening effect' or retardation in the transformation of austenite into a conglomerate of pearlite and ferrite. This effect will increase with the percentage of carbon and the smaller the size of the piece. The reheating to a temperature below the lower critical range, if not prolonged, will neither change the grain size nor allow of the coalescing of the excess ferrite or of the individual constituents of the pearlite, but will form a mass of irresolvable and intermixed pearlite and ferrite known as 'sorbite.' At the same time, however, it will give the maximum combination of large ductility, good strength and excellent machining properties. This method is of particular value in the annealing of tool steels, in which it has given most excellent results."

Double Annealing consists in heating the steel to a temperature considerably over the Ac_3 point, cooling rapidly to some point below the lower transformation range, then immediately reheating to a point slightly under or over Ac_1, and finally cooling slowly. This method is employed to relieve the most severe strains, which do not respond readily to ordinary annealing. The high first annealing temperature effaces the strains, while the rapid cooling prevents their returning. As this cooling tends to harden the metal, the second process is necessary to soften it and refine the grain, coarsened by the first operation, as much as possible. The second heating, of course, may be to a temperature just above Ac_3, when even better results should be obtained from the standpoints of both ductility and grain refinement.

Box Annealing: In many instances, especially with tool steel, it is important that the surface be protected from oxidation, or decarbonization. Some furnaces are now designed so that the object being heated may be surrounded by a reducing atmosphere, and so oxidation is prevented. Where such furnaces are not provided, it is the practice to pack the object pre-

paratory to heating in a metal box, called an annealing box, with some refractory material, such as sand, ground mica, etc., in the case of low carbon steel, or with some reducing substances, as for example, a mixture made up of a little charcoal with ashes, charred bone, etc., in the case of higher carbon steels, like the tool steels, for example.

Annealing Hyper-Eutectoid Steels: In annealing hyper-eutectoid steels, as in the case of hypo-eutectoid steels, one or more of these objects are aimed at; (1) release of strains, (2) softening in preparation for machining, and (3) change of structure. The first object may be accomplished by a simple reheating at temperatures considerably below those of the critical range. The second and third objects are more difficult to attain, for the treatment administered will be governed by the amount of the excess cementite and the form in which it exists. Thus, if the cementite is partly diffused, that is, does not exist as a net work or as spines and needles, and the grain size is small, conditions that may generally be expected in high carbon tool steels, the forging hardness may be largely removed by annealing at a temperature slightly under Ac, or between 600° C. and 700° C. If the steel is kept at this temperature any longer than is necessary to heat it thoroughly and uniformly throughout, the prolonged heating will cause the excess cementite, in amounts varying with the time, to coagulate. Such treatment will release the strains and soften the steel sufficiently for machining, but a second reheating above the critical point will be required to restore the normal structure. On the other hand, if the grain is coarse, making a complete change in structure desirable, it will be necessary to heat to a temperature in excess of the $Ac_{1\text{-}2\text{-}3}$ point, or above 725° C. For steels with a carbon content approximating 0.90 per cent., such heating will bring about a complete change of structure and give the finest grain-size obtainable through annealing. For steels with a carbon content considerably in excess of the eutectoid ratio the annealing may be done at similar temperatures, provided the excess cementite is more or less in solution. If the cementite is not in solution and a maximum refinement is desired, the steel may be oil quenched from a temperature somewhat over the $Ac_{1\text{-}2\text{-}3}$ range, and subsequently annealed at a temperature just below that range, or it may be normalized and annealed.

Normalizing and Spheroidizing: These are two processes applied to hyper-eutectoid steels in particular, though normalizing is often applied to hypo-eutectoid steels also. If the free cementite in the former steel exists as a network or as spines, which would make the steel difficult to machine, annealing at the usual temperatures ($Ac_{1\text{-}2\text{-}3}$) will not affect this cementite, but will simply refine the ground mass. In order to eliminate this free cementite, it is necessary first to normalize, that is, quench the steel from a temperature above that of the Ac_{cm} range. Usually, air cooling from a temperature of, say, 960° C., or 1000° C., will not permit the cementite to recoagulate. Lower carbon steels are heated to about the same temperature, but quenching is never required. Hence, in practice, normalizing

usually consists in heating the steel to the temperatures mentioned and cooling simply in air. The annealing may then be carried out at a temperature of 745° C. or over, to secure the refining of the grain size and complete softening of the steel. The heating for annealing should be just as short as possible in order to prevent the separation of the excess cementite again. The method given above may be modified for hyper-eutectoid steel by annealing at a temperature slightly under the lower critical range instead of over it. This method, however, is subject to the objection that the steel will not be refined, but will possess a large grain size on account of the high normalizing temperature. But on the other hand, the lower annealing temperature entirely prevents the formation of free cementite either as spines or as a network, and the excess cementite is thrown out, under these conditions, as little nodules or "spheroids," if the reheating temperature has been near the end of the lower critical range. Spheroidal cementite may also be obtained by cooling very slowly through the end of the Ar_1 transformation range. Spheroidizing is a great help in the machining of high-carbon steels. The structures obtained by annealing at these different temperatures are illustrated by Fig. 214, page 776.

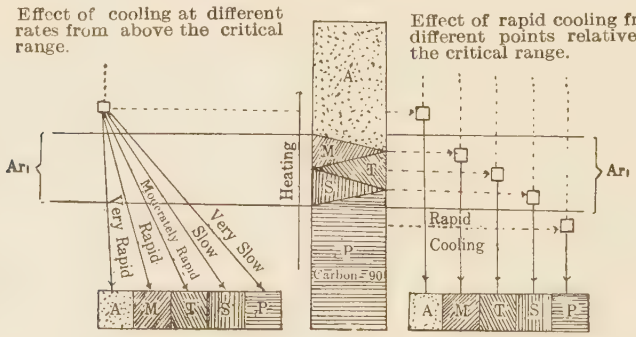
SECTION II.

HARDENING.

The Hardening Operation: The operation of hardening as applied to steels containing a sufficient amount of carbon consists fundamentally of the two operations of heating to a suitable temperature and suddenly, or rapidly, cooling. The heating may be accomplished in a number of ways, varying from costly and specially designed furnaces and baths heated with gas or electricity to the simple forge fire of the blacksmith; but the cooling is always brought about by plunging the steel into a suitable liquid, a process called quenching. Let the means be what they will, in properly hardened steel, the original structure, as it existed before the hardening process, such as coarse grain size, network, etc., has entirely disappeared and has been replaced by a new structure, totally different from that of the unhardened steel. To understand thoroughly the hardening process, a close study of the changes brought about by these two operations should be made.

Heating for Hardening: The structural changes that accompany the heating of steel through its critical ranges have already been briefly described in Chapter I, Part III. Graphically, these changes are represented in the central part of the accompanying diagram (Fig. 202), depicting the heating and cooling of a steel with a carbon content of about .90 per cent. From this evidence, it will be seen that the function of the heating is to bring about the proper change in structure so as to obtain (1) a condition favorable to the formation of austenite from which the hard constituents of the steel may be derived, and (2) the smallest grain

size, or highest refinement of the crystalline structure. From what has already been said, these structural changes can be obtained only by heating the steel above its critical range, where it changes from an aggregate of alpha ferrite and cementite to a solid solution of carbon in gamma ferrite, or austenite. Any attempt at hardening it at a temperature inferior to this range results in only a very slight, if any, increase of the hardness. Again, the metal should not be heated much above the top range, for then its grain structure is coarsened, as has been previously explained, also, and no additional hardness is imparted. Clearly, the best temperature to which the steel should be heated is one just above the critical range. The proper temperature to which plain carbon steels should be heated is the same as for the true annealing of the same steels. What has been said about the rate of heating and the influence of size of section in annealing also applies to heating for hardening. If any difference, additional emphasis should be placed on the uniformity of heating. The rule for heating may be put thus: Heat slowly, uniformly, and thoroughly, to the lowest temperature, and no higher, that will give the desired results. To meet these requirements, the final heating of steel for hardening is often, and commendably so, conducted in baths of molten lead or of the chlorides of sodium, calcium, potassium or barium.



Legend: P=Pearlite, A=Austenite, M=Martensite, T=Troostite, S=Sorbite.

FIG. 202. Diagram Depicting the Different Methods by Which the Five Different Structural Constituents of Eutectoid Steel May Be Obtained. (After Sauveur.)

Cooling for Hardening: Thus it is seen that heating for both full annealing and hardening are very similar, and that the changes wrought in the steel are the same in both cases. The main difference in the two operations is found in the rate of cooling through the critical ranges, at least. For hardening, this cooling must be very rapid, whereas in annealing it was characterized as slow. The transitions attending the transformation of austenite to pearlite on slowly cooling through the critical

ranges have been described. It will be recalled that this transformation is not instantaneous, nor is it direct, but takes place by stages through transitional structures called martensite, troostite, and sorbite, the order on slow cooling being from austenite, to martensite, to troostite, to sorbite, to pearlite. On heating, this order is reversed. It now may be explained that the secret of the hardening process is revealed by the fact that rapid cooling through the critical range may prevent this trans-

Table 68. Data with Reference to the Constituents of Hardened Steel.

Name	Nature	Occurrence	Temperature of Stability	Structure	Physical Properties
Austenite	Solid solution of FeC in gamma iron, Carbon content from trace to 2%.	Obtained in 1.50% C. steels when quenched in ice water from 1050° C. Occurs in steel containing 12% Mn. and 25% Ni. even after slow cooling.	Normally in region between A-1, 2, 3, and Acm. Becomes pearlite on cooling slowly past A_1: more rapid cooling forms martensite.	Polyhedral grains Face-centered cubic space lattice	Varies with carbon content. Very hard but softer than martensite. Non-magnetic. Densert constituent of any given steel.
Martensite	Solution of C or Fe_3C in beta iron, or an exceedingly fine-grained alpha iron with C or Fe_3C in atomic or molecular dispersion. Carbon content from trace to 1%	Obtained easily by quenching small bodies of hypereutectoid steel, in cold water. More difficult to obtain in low carbon steels. Chief constituent of hardened carbon tool steels.	Normally at slightly lower temperature than austenite. Changes into troostite.	Varies, Quenched from about 1000°C, it appears as fibers or flat plates lying parallel to three sides of a triangle. Body centered cubic space lattice.	Varies with carbon content. Hardest constituent of steel of eutectoid composition. A little less hard than cementite. Less dense than austenite. Magnetic.
Troostite	Mixture of Fe_3C in beta iron, or of crystallized Fe_3C and crystallized alpha iron.	Obtained by reheating martensitic steel to 400° C. or on cooling relatively slowly through critical range. Sometimes found in center of large objects quenched in water or oil.	Normally at lower temperature than martensite.	Slightly granular with sorbite and martensite intermingled and with ferrite and cementite in hypo- and hyper-eutectoid steels.	Intermediate between martensite and sorbite. Not so hard as martensite but stronger, more ductile, and a little denser. Magnetic.

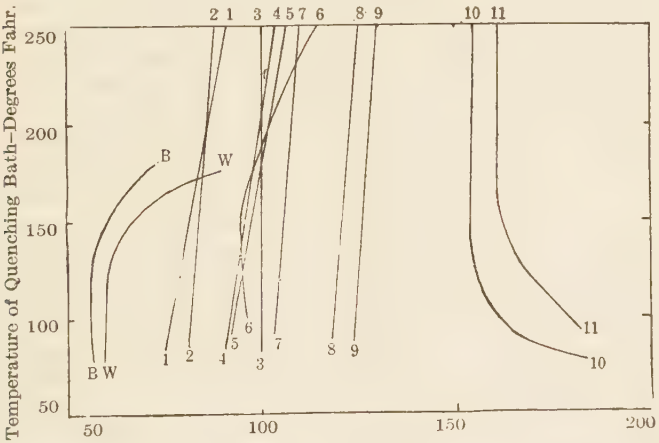
formation in part or in whole, depending on the rate of the cooling. Thus, by the most rapid cooling, the steel at atmospheric temperatures may consist largely of austenite, while a little slower cooling produces martensite; still slower, troostite; slow, sorbite; and very slow, pearlite. Incidentally, it may be remarked that the constituent found in the steel after treating also depends on the temperature within the critical

range at which the rapid cooling begins and the carbon content of the steel, because these constituents are formed at different temperatures and the presence of carbon retards the transformation. Since the properties of the cooled steel are imparted to it by the constituent which predominates, a study of the characteristics of these transitional constituents will, therefore, be of value. For the sake of brevity and convenience, this knowledge is put down in tabulated form on the preceding page.

Neither pearlite nor sorbite are, strictly speaking, constituents of hardened steel, but the latter, on account of its position in the transformation scale, forms the connecting link between hardened and annealed steel, hence may occur in both. Something about the nature and properties of sorbite have already been given, and it should here be recalled that it is the toughest constituent of steel. The transition from pearlite to austenite is admirably illustrated in the preceding diagram of figure 202.

Cooling or Quenching Media: Since the rate of cooling controls the hardening process, the selection of the proper quenching medium is a matter of much importance. The withdrawal of heat, the only function of a quenching liquid, from the metal immersed in it depends upon its quantity, its specific heat, its conductivity, its viscosity, its volatility, its latent heat of vaporization, and, to some extent, its initial temperature. The quantity and specific heat of the liquid control the quantity of heat the bath can absorb with a given rise in temperature. The viscosity affects the flowing properties of the liquid, hence the convection of heat by it, and therefore is a factor in the cooling properties of the liquid, for it is by convection and conduction that the heat is carried away from the steel to distant parts of the bath. The volatility indicates the temperature at which the liquid will become a vapor and form bubbles on the surface of the steel, which tend to retard the cooling. Evidently, if the latent heat, or heat of vaporization, is high the volatility may be relatively low, for then much heat is required to change the liquid to the gaseous state. Since the speed at which heat is transferred from one body to another varies directly as the difference in their temperatures, it is evident that the initial temperature of the quenching liquid must affect the rate of cooling. Thus, water, one of the most efficient media for rapid cooling in use commercially, has high specific and latent heats, and its viscosity is very low, properties favoring its cooling power, while its volatility and conductivity are both low, properties against it as a quenching agent. Then just next to water in cooling power comes mercury, which has a lower specific heat, a lower heat of vaporization and higher viscosity than water; but it is less volatile and is a very much better conductor of heat. Thus, while the one owes its cooling power to one set of properties, the other is almost as efficient because of an altogether different set. A solution of salt in water, brine, is said by some to be a little more rapid than water, and is superior to it for some articles of small section; but for articles of large section brine gives, in commercial practice, no better results than

water. Water sprayed under pressure upon the metal is a quicker cooling agent than either water or brine. After water, the chief quenching media in use commercially are the oils, all of which are much slower than water. An interesting experiment reported by Messrs. Matthews and Stagg[1] is intended to show the quenching properties of the various liquids that are employed in commercial hardening. In this experiment a suitable test piece of steel was carefully heated to 1200° F. and quenched in 25 gallons of the medium under examination, and the time required to cool the steel to 700° F. noted with a stop watch, as well as the rise in temperature of the medium. In each medium this operation was repeated successively until the medium had either reached its boiling point or a temperature of 250° F. The results of this experiment were then plotted somewhat as shown in the accompanying diagram.



Time in Seconds Required to Cool Test Piece from 1200° F to 700° F.

Legend:

B—Brine.
W—City Water.
1—New Fish Oil.
2—No. 2 Lard Oil.
3—Lard Oil in Use Two Years.
4—Boiled Linseed Oil.
5—Raw Linseed Oil.
6—New Bleached Fish Oil.
7—New Cotton Seed Oil.
8—Tempering Oil { 60% Cotton Seed. 40% Mineral.
9—Mineral Tempering Oil.
10—Dark Mineral Tempering Oil.
11—Very Viscous Tempering Oil.

NOTE. 10 and 11 are similar to cylinder oils.

FIG. 203. Diagram Illustrating Approximately the Quenching Power of Various Liquids. (Data by Messrs. Matthews and Stagg).

[1]See "Factors in Hardening Tool Steel" by Matthews and Stagg. American Society of Mechanical Engineers, 1915.

Combination Methods of Quenching: Besides the straight water or oil quenching and water spraying, many special quenching methods and media have been tried. Many of the latter are fakes, but the three following special methods of quenching have proved of great value. Thus, when high tensile strength is required, yet on account of the size of the piece or the chemical composition—manganese too high, for example—water quenching is unwise, the bath of water may be covered with oil to an equal depth, so that the piece upon being lowered into the bath is partly cooled in this oil, which then forms a film over the surface that retards the cooling by the water somewhat. This method is sometimes applied to large forgings, such as axles. For small tools a thin film of oil on the water suffices. Another method, used by some tool hardeners, consists of first plunging the tool into water to remove a part of the heat, then into oil till the cooling is complete. Information as to what is aimed at by this method is not at hand, but it is evident that the method is not so severe as straight water cooling and will not set up as severe quenching stresses. Where great toughness with little hardness is required, the article may be plunged into and forcibly submerged in molten lead, as this manner of quenching produces sorbite in steels under the eutectoid in composition.

Manner of Quenching: Much skill is required on the part of the operator in the quenching of steel to prevent cracking and warping. Both defects are due to unequal or non-uniform cooling of the different parts of the piece, and are more liable to occur, for obvious reasons, in bodies of large size or of irregular section. It is to overcome this danger that large axles are bored hollow before treatment. All large sections, if solid, and all articles of high carbon and alloy steels must be reheated immediately after hardening in order to relieve the internal stresses and strains, else incipient fractures may result. Warping will always occur in small sections, if the quenching is not uniform. As warping more often results when the piece is plunged into the quenching bath at an angle, it is always best to quench vertically, in the direction of greatest length, whenever such procedure is possible. Sometimes, these defects can be avoided by removing the article from the quenching bath as soon as its temperature has reached 250° C. (482° F.).

Progressive Hardening: Progressive, or differential hardening, is accomplished by quenching only a part of the object. In such a method the heat is slowly withdrawn from the part farthest from the quenching liquid, but more and more rapidly as the part quenched is approached, so that the steel becomes progressively softer and tougher from the hardened part. By withdrawal of the piece before cooling is complete, the heat in the unquenched part may be made to temper the hardened portion. In this method, care is needed to avoid hardening, or quenching, rings, which form if the piece is held in the quenching bath at a uniform depth. To avoid them, the piece should be raised and lowered during the quenching. This method is employed in treating such tools as anvils, die blocks, edged tools, pointed tools, etc.

Hardening Eutectoid Steels (C. .80 to .90 per cent.): Steel of eutectoid composition possesses the maximum hardening power, that is, the difference in hardness between the quenched and unquenched article of eutectoid composition is greater than that in any other grade of the plain steels. So, this statement does not mean that quenched eutectoid steels are the hardest steels, for hyper-eutectoid steels may show much greater hardness both before and after hardening than eutectoid steels, due to the presence of free cementite or to more highly carbonized martensite, but their gain in hardness on quenching is less. It is clear that eutectoid steels should be hardened from a temperature just above Ac_1, that is, 750° to 800° C. (1382° to 1472° F.), for at this temperature the carbon, being in solution and thoroughly diffused, is able to exert its full influence, and the grain structure is at its finest. For the maximum hardness, the metal should then be quenched as suddenly as possible in water, by which treatment the austenite is changed into a fine grained martensitic or troostito-martensitic structure, depending upon the size of the article and other incidental conditions. In order to avoid the danger of cracking, some operators withdraw the article while it is still at a temperature of about 250° C. (482° F.), while others prefer to quench in oil, when troostite may be the predominating constituent if the piece is of large size.

Hardening Hyper-Eutectoid Steels (.90 to 1.40 per cent.): Steels that contain more than .90 per cent. carbon are also hardened by heating just above $Ac_{3\text{-}2\text{-}1}$, or in other words, at the same temperature as steel of eutectoid composition, the reason for which is readily seen by a little reflection. To cite an example, suppose the steel to be hardened has a carbon content of 1.30 per cent. Such a steel in its natural state is composed approximately of 93 per cent. pearlite and 7 per cent. free cementite. To cause both pearlite and free cementite to change to austenite would require the steel to be heated above Ac_{cm}, about 950°, but such a high temperature would result in a decided and undesirable coarsening of the grain size, which is avoided by heating only above $Ac_{3\text{-}2\text{-}1}$. Besides, quenching from this lower temperature would give a harder steel than would be obtained in the first instance. For, supposing the quenching is such as to produce martensite, in the first case, the hardened steel would be composed of martensite only, whereas in the second instance it would be made up of 93 per cent. martensite and 7 per cent. free cementite, which being harder than martensite, would impart additional hardness to the quenched steel. When for any cause it is desirable to avoid the presence of any free cementite, the metal may be heated above Ac_{cm} and cooled in molten lead, then reheated to slightly above Ac_1, and quenched as usual. The quenching in lead prevents the re-formation of free cementite and is not severe enough to cause cracking or warping, while the reheating to Ac_1 accomplishes the grain refinement so much to be desired in these steels.

Hardening Hypo-Eutectoid Steels (C. .30 to .80 per cent.): Steel containing less than .30 per cent. carbon cannot be materially hardened by any of the ordinary commercial methods of quenching on account of the separation of ferrite from the solution, which takes place to some extent even with the most rapid methods of cooling. For hardening hypo-eutectoid steels with a higher carbon content, two methods may be employed. First, the metal may be heated slightly above Ac_1 and quenched, when only the pearlite of the steel will be affected, it being changed into martensite or troostite according to the rate of cooling, and the free ferrite will undergo no refinement at all. Evidently, the second and better plan is to heat the metal above Ac_{2-3}, when its entire bulk changes into hardenable austenite, which on quenching rapidly may be converted into martensite or at least troostito-martensite. While this martensite, because of its lower carbon content, is not so hard as the martensite formed from the pearlite in the first method, the steel as a whole will be harder and certainly more uniform and of a much finer grain structure, because the original network of coarse ferrite will have been absorbed and refined.

Structure of Martensite and Theory of Hardening: Many theories have been advanced, from time to time, to account for the hardening of steel, but the one recently proposed by Jeffries and Archer[1] appears most plausible, for this reason: From the preceding description, it should be evident that the hardening of steel by heat treatment alone depends upon the fact that the rapid cooling, combined with the retarding influence of carbon, prevents the complete transformation of the austenite into pearlite, giving rise to the series of intermediate structures designated as martensite, troostite, and sorbite. Of these intermediates, martensite is the hardest, and the only structural constituent of a steel in its hardest state. Any theory of hardening, then, must be based on the constitution and structure of martensite, and the theory of Jeffries and Archer is so founded. According to their theory, martensite consists of very fine-grained alpha iron in which the carbon is distributed in a most finely divided state. The grains of alpha iron are so small they are submicroscopic in size, and the carbon is present either as elementary carbon in atomic dispersion or as cementite in a state of molecular dispersion. Now, hardness depends upon the resistance of the metal to deformation, and deformation takes place by a process of slipping along the slip planes of the crystals. In process of deformation, slippage is stopped on a slip plane partly by resistance of disorganized atoms adjacent to the slip plane, but mainly through end resistance. This end resistance is supplied by two agencies, namely, the grains themselves and the presence of particles of a hard foreign substance. How such particles of a hard substance will give a "key effect," and act as a stop to movement along a slip plane is

[1]For a full discussion of this theory see "The Science of Metals", Chapter XII, by Zay Jeffries and R. S. Archer. Published by McGraw-Hill Book Company, New York, N. Y.

readily apparent, and the action of the grains, up to a certain point, is similar, because, since the orientation of each grain differs from that of its neighboring grains, any force producing movement in one grain must be resolved into two or more component forces acting at angles to produce slip in the neighboring grains. Hence, the slip producing movement in one grain is stopped until the component forces are equal to that required to produce slip along the new planes. Evidently the finer the grains the greater their ability to produce slip interference becomes. An extremely fine grain structure in the presence of carbon in atomic dispersion, or as carbide particles, therefore, is sufficient to account for the extreme hardness of martensite. So, it only remains to show that martensite does possess this structure. That martensite is composed of alpha iron is indicated by the volume and thermal changes that accompany the passage of austenite into martensite and by the fact that martensite is magnetic. Finally, if martensite is examined with the X-Ray spectroscope, it gives a pattern like that of alpha iron. As the body-centered cubic space lattice is characteristic of crystalline alpha iron, this pattern is taken as positive proof that the iron in martensite is in the form of crystallized alpha iron. The fact that under the microscope martensite appears to have no grain structure is no evidence that it is not crystalline in form, for the grains may be so small that they are invisible even under the highest power of the microscope. As to the condition of the carbon in martensite, the evidence is indirect and less convincing, but the results of recent researches by various investigators would indicate that in freshly formed martensite it is present in a state of atomic dispersion, but that under certain conditions some or all of the carbon combines with iron to form cementite, which remains dispersed in very finely divided form.

Formation of Martensite: Perhaps a review of the changes that take place in heating and cooling steel for hardening will assist the reader in getting a clearer understanding of this theory, which is intended to explain not only the nature of martensite but the fundamental causes of the hardening of the steel as well. In addition, such a study will supply knowledge of great practical value. Starting with a high carbon steel in the pearlitic condition, it is found that on heating this steel to its critical point, the metal loses its magnetism, absorbs heat, and contracts in volume. Andrew, Rippon, Miller and Wragg[1] have shown that, as the metal passes through the temperature range from 740° C. to 800° or 900° C., according to the carbon content, two opposing forces act to produce change in volume, namely, a contraction due to the alpha-to-gamma transformation and an expansion due to the absorption of iron-carbide. From these facts, some authorities conclude that the iron carbide is decomposed and that the carbon is held in solution, that is, it is in a state of atomic dispersion, with the carbon atoms occupying interstitial spaces

[1]See "The Effect of Initial Temperature upon the Physical Properties of Steel", by J. H. Andrew, J. E. Rippon, C. P. Miller, and A. Wragg. Journal Iron and Steel Institute, Vol. CI, 1920.

among the iron atoms within the grains. If now the steel be cooled slowly, it will pass into pearlite, at about the same temperature for the change on heating, but if it is quenched, the transformation range is lowered and the austenite may remain unchanged or be converted into troostite, martensite or a mixture of the two. Portevin and Garvin[1] have established what they term a critical cooling rate in quenching. If the speed of cooling is below this critical rate, the transformation is lowered to about 600° C., and troostite is formed, while if the speed of cooling exceeds this critical rate the transformation point is lowered to about 300° C., (572° F.) or lower, and martensite is formed. All these facts are represented graphically in the first three columns of the diagram on page 691, Fig. 204. With this change from austentite to martensite, the steel becomes magnetic, expands in volume, and evolves heat. The amount of the expansion is about the same in value as the alpha-to-gamma contraction on heating, but without the carbide expansion, while the heat evolved is less than that evolved at $Ar_{3\text{-}2\text{-}1}$ on cooling slowly or that absorbed on heating through $Ac_{3\text{-}2\text{-}1}$. If now, the freshly formed martensite be allowed to age for a long time at room temperature or for a shorter time at a higher temperature, say 100° C., it gives off heat, becomes harder, and contracts in volume. Also, upon being treated with hydrochloric acid such steels give off nearly all of their carbon as hydrocarbon gases, while the same annealed steels give off a smaller proportion. From this evidence and that supplied through the X-Ray spectroscope, it seems most probable that the formation of martensite takes place in the following manner: Upon cooling the solid solution, austenite, to about 300° C. at any rate greater than the critical, the gamma-to-alpha iron transformation takes place, but the cementite reaction does not immediately occur, and, since the alpha iron is formed at a temperature far below its normal crystallization temperature, an excessively large number of nuclei are formed, as in supercooled solutions, and very little grain growth takes place. At the time of its birth, then, martensite consists of very fine grained alpha iron with the carbon atomically dispersed. Since carbon is much less soluble in alpha than in gamma iron, there is a strong tendency for it to form cementite. But, as the formation of cementite involves movement of the atoms, the reaction takes place very slowly and only to a limited extent at atmospheric temperatures, and the cementite formed must remain in a state described as molecular dispersion. The formation of the cementite particles will cause the steel to become harder, because they exert a greater key effect than carbon atoms.

Practical Value of the Theory: These facts are cited here not merely to support a very probable theory but mainly for their practical value. Properly interpreted and applied, the theory, as well as the facts, may point the way to an improvement in the practice of the heat treat-

[1]See "The Experimental Investigation of the Influence of the Rate of Cooling on the Hardening of Carbon Steels", by A. M. Portevin and M. Garvin, Journal Iron and Steel Institute, Vol. XCIX, 1919.

ment of steel. For example, the theory explains perfectly the cause of the familiar surface cracks, known as water cracks or quenching cracks, and other defects developed in quenching. That these defects are due to internal stresses set up by the rapid cooling has long been evident, but the exact cause or the nature of these stresses has been largely a matter for speculation. In hard quenching a piece of fairly large section, say a one-inch round, the heat is withdrawn from the metal near the surface faster than it can be conducted from the interior. Consequently, this outer layer, being cooled more rapidly than the metal near the center, retains all the carbon in atomic dispersion, while that within permits some or all the carbon to pass into the carbide form. This difference in the carbon-to-carbide transformation causes a difference in the expansion of the two portions, throwing the outer portion under compression and the inner portion under tension. Since this difference is produced at the time of the transformation, either portion may "give" slightly without producing ruptures. When the piece has cooled to atmospheric temperatures, however, it is harder, less ductile, and more rigid. Now, if the carbon atomically dispersed in the outer layer of metal were all converted into carbide, a contraction would occur equal to the carbide expansion above the critical range, which would throw the central portion under compression and the outer portion under tension. Since migration of atoms is necessary to this reaction, it takes place very slowly at atmospheric temperatures. As this action progresses, the tension on the outer portion increases, and, at the same time, this portion becomes harder and less ductile, so that it is but a matter of time until rupturing must occur in this part. This rupturing appears as fine irregular cracks over the surface. The remedy suggested by this explanation is to remove the article from the bath as soon as it has cooled through the hardening range, i. e., as soon as it has cooled to about 250° C. (482° F.). Experiments indicate that stopping the quenching at this temperature, i. e., allowing the piece to cool more slowly from this point, results in little, if any, reduction in the hardness. Likewise, by removing the steel from the quenching bath just before it has reached the transformation temperature of about 300° C. (572° F.), it may be subjected to slight mechanical working, such as straightening, without injury, and still be obtained in a comparatively hard state on cooling to room temperature. The reason for this is to be found in the fact that austenite is softer and much more ductile than martensite.

SECTION III.

THE TEMPERING OF HARDENED STEEL.

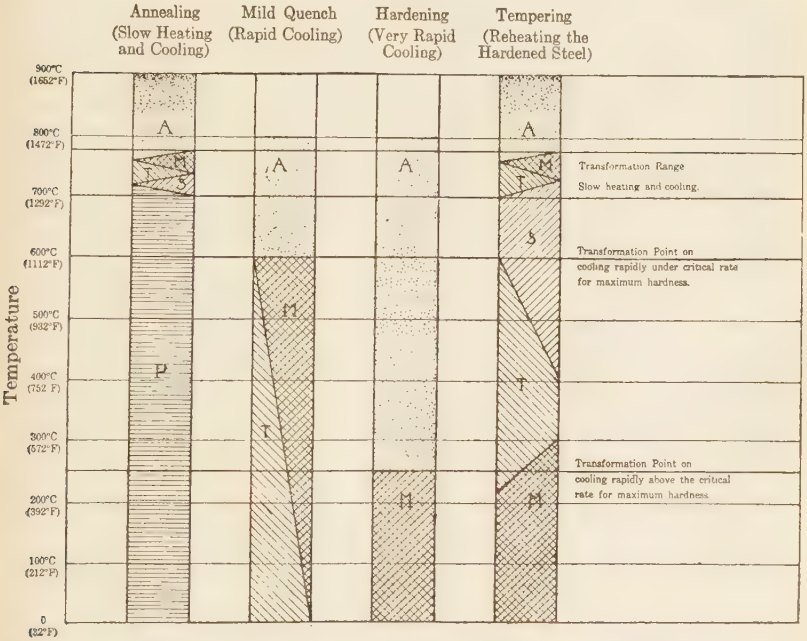
The Tempering Process: Tempering, sometimes spoken of as drawing-back or simply as drawing, consists in reheating the metal after hardening to some temperature below the critical ranges, and may have for its primary object (1) the regulation of the hardness and brittleness of the steel, (2) the toughening of it, or (3) the release of the hardening stresses. In tempering, the release of the internal stresses set up by the hardening process is always aimed at, whatever may be the other results sought, for the metal is incapable of giving its best service as long as these or similar stresses exist. This result is usually accomplished by the heating in the tempering process, for heating even to the temperature of boiling water will relieve these stresses to some extent. This fact is often taken advantage of to relieve stresses when it is not desirable to soften the steel to the extent that higher heating would involve.

Nature and Theory of Tempering: That reheating hardened steel above 100° C. causes it to become progressively softer until the full annealing temperature is reached, has been known and used for centuries, but an entirely satisfactory explanation of the phenomenon was lacking until Jeffries and Archer had formulated their theory of hardening. As indicated in the preceding section, according to this theory, it is postulated that martensite in its hardest condition is composed of exceedingly small grains of alpha ferrite and carbide in a state of critical dispersion therein. In this condition martensite will remain unchanged at room temperatures for an indefinite period of time. Upon reheating the steel to about 200° C. (392° F.), or slightly over, the molecular energy is increased to a point that permits the cementite to crystallize also, thus forming troostite. The evidence for believing that this is the change that takes place is found in the fact that the steel contracts, the total contraction varying with the carbon content and comparing with the carbide expansion noted above the critical range[1]; that it evolves heat[2],—the total amount of heat evolved up to 400° C., being proportional to the carbon content; that the steel is easier to etch with acids; and that on dissolving the steel in hydrochloric acid a smaller proportion of the carbon is liberated as hydrocarbons than before tempering. This segregation of cementite continues, with an attendant softening effect, until at 400° C. (752° F.), it is practically complete, grain growth has begun, and sorbite begins to form. Above this temperature grain growth in the alpha iron is fairly rapid and the cementite collects in tiny globules, so that at about 620° C. (1148° F.), the steel becomes almost as ductile

[1]Andrew, Rippon, Miller and Wragg: Journal Iron and Steel Institute. No. 1, 1920, pp. 561-64.

[2]Honda: Chemical and Metallurgical Engineer. November 30, 1921.

as, but remains much stronger than, annealed steel, because the segregation is less extensive and the grain size is still much smaller. This process will continue with little noticeable change in the physical properties until the critical range is reached. Any higher heating, then, carries the transformation into the critical ranges, where the order of transition is reversed, sorbite passing into troostite and then to martensite, which, as the temperature, on rising, emerges from the range, becomes austenite. The following diagram, Fig. 204, will aid in understanding these changes when they take place under different conditions.



Legend, A=Austenite, M=Martensite, T=Troostite, S=Sorbite, P=Pearlite.

FIG. 204. Diagram Depicting the Constituents Formed on Slowly Cooling and Quickly Cooling Steel of Approximately Eutectoid Composition and on Reheating the Hardened Steel.

Heating and Cooling for Tempering: Evidently then, all heating for tempering is conducted below the critical range. By properly adjusting the temperature, the transition described above may be arrested at any stage desired, and any combination of physical properties of which the steel is capable may be obtained. As to the manner of heating, this is immaterial in so far as it may effect the mechanical properties, if proper facilities are provided for controlling the temperature accurately. Liquid

baths give such control of the temperature, and are commonly used on that account. For temperatures below 350° C. (662° F.), oil baths may be employed, while for higher temperatures lead baths are generally used. As to the manner of cooling from the tempering temperature, this depends upon the kind and grade of steel. Medium carbon steels (carbon under .60%) may be cooled in water without noticeable effects, but higher carbon steels and alloy steels show a modification of mechanical properties on cooling in air and in water. Some articles, springs, for example, are injured by cooling in water.

Methods of Determining Tempering Temperatures: The original method of estimating tempering temperatures is by color. Thus, if a piece of hardened steel is brightened or polished with a piece of emery, sand stone, or other suitable means and is then slowly heated in contact with air, the color of the brightened surface will, due to the formation of a surface film of oxide, undergo a series of color changes, called temper colors, ranging from faint yellow to blue, which will be characteristic of the different temperatures reached by continued application of heat. That these colors are indicative of a known temperature or at least a definite condition of the hardened steel is generally accepted; but it is evident that the method is subject to the objection that differences in distinguishing different colors, or shades of color, is bound to occur among different operators. Distinction of these colors is also affected by different light conditions. The same temper will not give the same color in a dimly lighted room as in a well lighted one. While these shades are hard to describe, the color corresponding to the same temperature often being differently described by different individuals, the following table will give some idea of the colors corresponding to the different temperature changes.

Table 69. Tempering Colors and Temperatures Corresponding to Them.

Pale yellow	220 deg. C.	Pale blue	297 deg. C.
Straw	230 " "	Dark blue	316 " "
Golden yellow	243 " "	Red in the dark	400 " "
Brown	255 " "	Red—indirect sunlight	525 " "
Brown dappled with purple	265 " "	Red in sunlight	580 " "
Purple	277 " "	Dark Red	700 " "
Bright blue	288 " "		

That the color method has its limitations is now well established, so other methods are being developed on a more scientific basis. These methods involve the use of sand baths or liquid baths, such as oil, molten lead, or alloys, fused salts, etc., for heating the steel and the use of pyrometers for controlling the temperature, and aim at the elimination of the personal equation in the results obtained. Seeing that the tempering action often takes place very rapidly and that a difference of 15° or 20°

of temperature will often spell success or failure, such appliances would appear to be a very necessary part of the equipment of the modern heat treating shop.

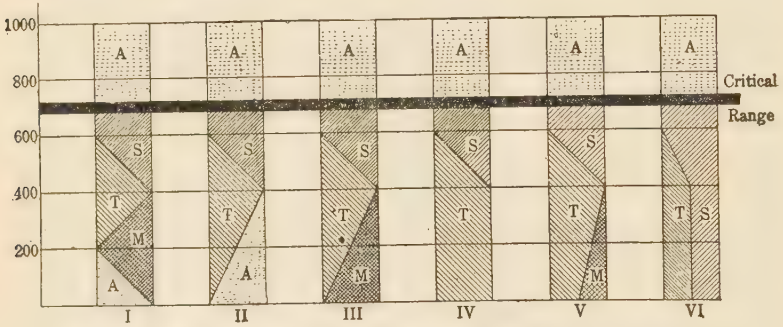
Influence of Time in Tempering: From what has been said about the transformations wrought in the tempering process, the reader might infer that the time the steel is kept at the tempering temperature would exert no influence. Lest such should be the case, occasion is taken to explain that, contrary to this inference and, in fact, to the common belief, maintaining the metal at the tempering temperature for a considerable length of time will result in producing additional tempering. This fact is evidenced by the change of the tempering colors at constant temperature. Thus, it has been ascertained that the temper color, instead of remaining the same at a given temperature, advances in the tempering color scale as it would if the temperature were being raised, which phenomenon would appear to indicate that the temper colors are indicative of the tempering condition of the steel rather than of the temperature. For example, by heating a steel to 277° C., where its temper color is purple, and keeping it there till its color is bright blue, a temper corresponding to the temperature 288° C. is obtained. According to some investigators, however, the temper will not follow the color to the end. They maintain that each temperature has a maximum temper effect, which is reached quicker and quicker as the temper temperature is raised.

Physical Properties Affected by Tempering: It is to be remembered that besides the hardness, the other physical properties of the steel are likewise affected by tempering. Thus, as the hardness and brittleness are decreased, the tensile strength and elastic limit will follow the hardness closely and be correspondingly decreased, while the ductility, i. e., elongation and reduction in area, will be increased, though not following in the wake of the hardness with the same regularity as the tensile strength and elastic limit. (See table 70, page 697)

Tempering the Steels of Different Structural Composition: Seeing that the hardening process has developed a certain structure in the steel, it may be well, in turning to the practical application of the principles and theories of tempering the hardened steels, to consider this phase of the subject from the standpoint of their structural composition. The diagram, Fig. 205, on the next page, is intended to depict the tempering of all the hardened steels.

Tempering Austenitic Steels: As has already been shown, austenite does not occur in steels hardened by any of the commercial methods. Hence, a lengthy discussion of the tempering of austenitic steel is out of place in this study. It may be pointed out, however, that instead of passing into martensite then to troostite, as shown at I in the diagram, austenite

may on tempering, pass directly into troostite as indicated at II. The diagram shows that austenite begins to be transformed at a very low temperature, being completely converted into martensite at 200° C. or into troostite at 400° C.



Legend: A=Austenite, M=Martensite, T=Troostite, S=Sorbite.

Fig. 205. Diagram Depicting the Tempering of Hardened Steel. (By Sauveur.)

Tempering Martensitic Steels: If steel of high carbon content has been fully hardened by quenching rapidly, as in water, it consists mainly of martensite, if other conditions were at all favorable. This constituent is more stable than austenite, and on tempering will begin to change to troostite below 200° C. and this transformation is complete at about 400° C., as shown at III on the diagram. Recalling the properties of troostite, it will be seen, then, that tempering between these two points results in a material decrease of the hardness and brittleness accompanied by a decrease also of tensile strength and elastic limit, while some increase in the ductility will be noted. It is to be observed that just as martensite predominates in the structure of hardened steels, and pearlite, of annealed steels, so the presence of troostite indicates tempering, either as a separate reheating process or by regulating the cooling in the hardening operation, as for example, in oil quenching, which is often called oil tempering on this account.

Tempering Troostitic Steels: Commercially hardened steels, especially those quenched in oil, will sometimes show large proportions of troostite. From the diagram it will be seen that to temper this steel will require a temperature of at least 400°, the temperature at which it begins to be changed into sorbite. At 600° C. the transformation of troostitic sorbite is complete. Tempering here results in a marked toughening of the steel with loss of much of the hardness. Hence, as explained below, tempering between these temperatures is called toughening by many of the heat treating experts. However, troostite steels produced by quenching often contain considerable martensite. When such is the case the steel may be softened by reheating to about 400° C., when the martensite will be destroyed.

Sorbite: As this constituent occurs at the top of the tempering range, sorbitic steels cannot be tempered. Furthermore, as these steels are not produced by the regular hardening methods, they are not properly considered in connection with tempering.

SECTION IV.

THE TOUGHENING OF STEEL.

Toughening is the term applied to certain treatments given usually to steels of medium carbon content (C. .35% to .60%) in which strength and toughness, rather than hardness and toughness, are the properties sought. It is a treatment applied to railroad axles, piston rods, and other articles subjected to fatigue, impact and dynamic stresses in service. As practiced by the Carnegie Company, toughening consists in heating the steel to temperatures varying from 775° C. to 850° C., depending upon the chemical composition, quenching in oil or water, and then drawing back to such high temperatures, 450° C. to 650° C., that little, if any, of the hardness due to the quenching remains. According to this practice, therefore, toughening is a quenching and tempering process applied to medium carbon steels.

Benefits of Toughening: Compared with annealing, toughening has an advantage in that both the strength and ductility of the steel may be increased to the limits of which the steel is capable. In annealing, strength is sacrificed for ductility, but in toughening, the relation of these properties may be nicely controlled. The effect of the quenching operation is to give the greatest refinement of the grain and to develop the maximum strength of which the steel is capable. The effect of the draw back is to relieve all strains due to the quenching, and, without coarsening the grain, develop the ductility, which will gradually increase, with a partial loss in strength, of course, as the temperature of the draw back is raised. Between 500° and 600° C. the draw back produces a steel composed entirely of sorbite, which is the structure that gives the highest combination of strength and ductility. The pearlite produced by the usual annealing methods is both less strong and less ductile than sorbite. One feature of the toughening operation is to increase the ratio of the elastic limit to the ultimate, or tensile, strength. Thus, while in natural and annealed steels of toughening grade this ratio is approximately 3:6, in properly toughened steel it is about 4:6. In view of the fact that it is the elastic limit that actually measures the working strength of the steel, this effect of toughening is worthy of careful consideration. The sorbite structure also enables the steel to withstand fatigue or vibratory stresses better than any other structure.

Quenching for Toughening: As indicated above, either oil or water is used as a quenching medium for toughening. Both media have their

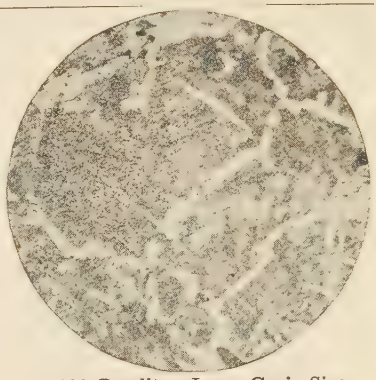
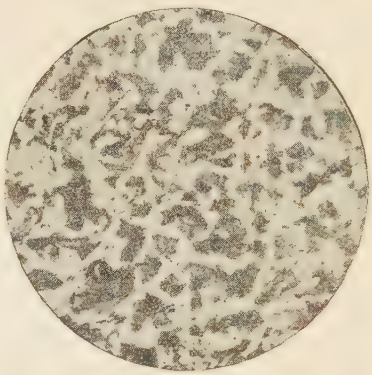
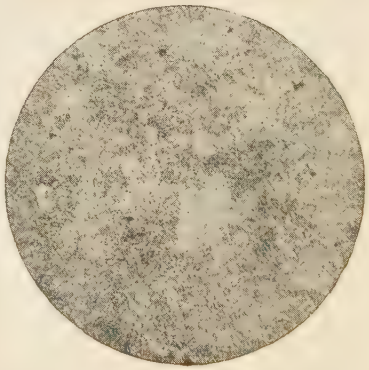
Ladle Analysis	Treatment	Mechanical Properties	Structure
C. .49% Mn. .66% P. .020% S. .026%	as forged	Ultimate Strength 96,370 lbs. Elastic Limit 49,310 Elongation in 2″ 20.5% Reduction of Area 34.7%	 x 100. Pearlite—Large Grain Size.
C. .48% Mn. .54% P. .020% S. .036%	Annealed Heated to 830°C and cooled in air	Ultimate Strength 85,040 lbs. Elastic Limit 44,920 lbs. Elongation in 2″ 23% Reduction of Area 37.8%	 x 100. Sorbitic Pearlite—Grain Size Good.
C. .49% Mn. .66% P. .020% S. .026%	Quenched and tempered Heated to 825°C and quenched in water Drawn back at 585°C	Ultimate Strength 97,200 lbs. Elastic Limit 62,720 lbs. Elongation in 2″ 25% Reduction of Area 59.8%	 x 100. Sorbite—Grain Size Excellent.

Fig. 206. Showing Change in Structure and Condition of Constituents in Steel Due to Heat Treatment, with the Accompanying Changes in the Physical Properties. Specimens taken from large forgings, six inches in diameter, midway between center and outside, all from articles of the same size and design and forged in the same manner. (Micrographs by O. M. Ash).

advantages and disadvantages. Water is the more rapid and drastic medium, and on this account, is more liable to develop cracks in the steel, hence some heat treaters recommend that only oil be used. On the other hand, a deeper penetration of the effects of the quenching and greater tensile strength and elastic limit are obtained with water than with oil, thus making it easier to meet specifications calling for high tensile properties. Therefore, others will prefer water quenching under certain conditions. In selecting the quenching medium, it is evident that much depends upon the article, its shape, size, and the grade of steel it is made of, and much upon the skill of the operator. All these features of toughening are brought out in Fig. 206 and table 70.

Table 70:[1] Illustrating the Effect of Various Heat Treatments upon the Mechanical Properties of Medium Carbon Plain Steels.

Chemical Composition; C. .38%, Mn. .55%, Si. .05%, P. .024%, S. .050%.

Description of Pieces Treated; one inch rounds, 29 inches long; 14 pieces, all from same billet.

Description of Test Pieces; One test piece from each of the 14 pieces, turned to a diameter of ½ inch, as in Fig. 111, page 422.

Heat Treatment		Physical Tests					
Hardening and Refining Deg. C	Anneal and Draw, Deg. C	Tensile Strength	Elastic Limit	Elongation in 2" %	Reduction in area %	Brinell Number	Scleroscope Test
As Rolled	....	85,000	50,000	30.0	48.9	163	25
Heated to 760° and cooled in furnace		74,000	42,500	32.0	54.7	134	23
Heated to 815°	427°	100,000	67,000	21.0	53.9	179	30
quenched in oil	482°	98,000	66,000	23.5	52.8	170	29
.....	538°	90,000	59,000	26.5	54.7	170	29
.....	593°	89,000	58,000	26.5	63.5	170	29
.....	649°	75,000	53,000	33.5	64.7	156	27
.....	704°	71,000	51,000	34.0	59.3	137	25
Heated to 815°	427°	110,000	81,000	19.0	46.0	223	35
quenched in	482°	103,000	71,000	22.5	54.7	192	33
water	538°	95,000	68,500	23.5	61.6	187	32
.....	593°	89,000	63,000	28.5	63.0	179	29
.....	649°	82,000	57,500	30.5	65.4	156	26
.....	704°	73,000	51,000	34.0	59.8	143	25

[1]The data for this table, as well as that for tables 73, 76, and 77, were supplied by Henry Wysor, of the Bethlehem Steel Company.

SECTION V.

CASE HARDENING.

The Process of Carbonizing Iron: It is a well known fact that if a bar of wrought iron or soft steel be heated to a temperature close to or above the critical range in contact with carbonaceous materials and within a suitable receptacle from which air is excluded after the heating is started, the bar of metal will absorb carbon, the amount so absorbed depending upon the time the bar is kept in contact with the carbon, the temperature maintained during the operation, the nature of the carbonaceous material, and the initial composition of the bar itself. This characteristic of iron with respect to carbon was first made use of in the manufacture of steel from wrought iron by the cementation process, then for the surface carbonizing of armor plate, and finally for case hardening, or surface carbonizing, smaller articles. Essentially, case hardening is but a special application of the cementation process, in which the articles treated are but partially carbonized and the case extends but a short distance from the surface, leaving the central portions of the articles unchanged in chemical composition. Thus, while the chief principle of carbonizing iron has been known and made use of for years, it is only within recent times that case hardening has become a process of commercial importance.

Application of Case Hardening: The result sought, in most cases where case hardening is employed, is the production of a hard, wear-resisting surface upon a tough, ductile core. It is, therefore, applied to many tools, to gears, to ball bearings and to various parts of automobiles, airplanes, bicycles and the like—in fact, wherever a combination of toughness and lightness with a wear-resisting surface is desired. On account of the wide application of the process and the fact that the art has not yet reached the stage of fullest development, a wide variation in the methods of applying the process is to be expected. This condition makes the subject a difficult one to deal with briefly and at the same time satisfactorily. In the following paragraphs, an attempt has been made to give a summary of the facts as revealed by the work of many investigators who have published or otherwise made known the results of their experiments and experience. Only general features are thus dealt with, because the working out of details is largely a matter to be determined by experience.

The Two Periods of the Case Hardening Process: In order to obtain the greatest benefits from case hardening, it is necessary that the carbonization be succeeded by proper heat treatment, or that the carbonizing process be considered as a part of a special heat treating process. The chief factors that control the carbonization have already been enumerated. Since a relatively high temperature is employed in the carbonizing process and the cooling, at the end of the carbonizing period, is usually slow, the steel, as a whole, is in its softest condition, and has a large grain structure.

Therefore, the heat treating part of the process must combine a grain refining operation for low carbon steel with a hardening and grain refining treatment for high carbon steels.

Kinds of Steel Suitable for Case Hardening: In general, the composition of the steel for case hardening is limited by the desire to eliminate any elements that produce brittleness in the core, and also any that tend to retard the absorption of carbon by the steel. The elements that may be permitted and those that should be avoided in steel for case hardening will, therefore, be easily recognized after a study of the two succeeding chapters which are devoted to the effects of the elements upon the properties of steel. For convenience, however, a list of the elements with data concerning their case hardening properties is given here.

Carbon: Since the tendency of carbon, especially when present in any amount greater than .25 per cent., is to increase the brittleness, .30 per cent. is the limit to which the carbon in steel for case hardening may rise. Therefore, the carbon content of steels for this purpose ranges from .08 to .25 per cent. For ordinary purposes a carbon content of .08 to .15 per cent. is most satisfactory. However, as steel of this grade is difficult to machine so as to give a smooth surface, and a fairly strong core is desirable for some kinds of work, a carbon content of .15 to .25 per cent is frequently specified. Needless to say, the higher carbon grade requires more care in treatment than the low carbon grade.

Manganese: While manganese increases the ability of the steel to absorb carbon, on account of its tendency to make the case brittle and sensitive to shock, the per cent. of this element is generally kept below .50, though steel with a manganese content of .70 per cent. is sometimes employed.

Silicon: When the silicon content is raised to 2.0 per cent., the steel refuses to absorb carbon, hence the steel should be kept as free of this element as possible. The highest limit for silicon to give commercially satisfactory results is about .30 per cent.

Phosphorus and Sulphur: The phosphorus and sulphur content of the steel should be as low as possible, not over .05 per cent. for each of these elements.

Nickel: Nickel strengthens and toughens steel, but retards the carbonization of the metal. The rate of penetration is lowered in proportion to the amount present, so that in a steel with a nickel content of 5 per cent., the rate of penetration, using solid carbonizing materials, is about half that in the plain low carbon low manganese steels. But, offsetting this disadvantage, nickel steels possess certain peculiarities of structure and increased toughness, which make them desirable for carburizing purposes.

Vanadium: This element also lowers the rate of carbon penetration, but since it is present in very small amounts, its action in this respect is less pronounced than in the case of nickel.

Chromium: The low carbon chrome steels, especially those containing about 0.5 per cent. chromium, are well adapted to case hardening, for the chromium not only increases the rate of penetration and the concentration of the carbon in the case, but also materially reduces the grain size. Furthermore, this amount of chromium does not harden the case nor render it brittle beyond that which would be obtained by slightly increasing the carbon content of the plain carbon steel.

Molybdenum increases the rate of penetration and the concentration of the carbon, and is otherwise similar to chromium for case hardening.

The Carbonizing Agent: Many investigations have been conducted to determine just what the carbonizing action is. Originally, it was held that the carbon was absorbed directly at the surface of the metal and there dissolved, the dissolved carbon being then disseminated towards the interior. That dissolved carbon may move about, or diffuse, within the metal is accepted, but it has been proved that carbon alone in contact with iron has only a slight carbonizing action and that, for commercial carbonization, the presence of carbon bearing gases is necessary. By diffusing into the steel where they may react with the iron, these gases act as carriers of the carbon. The gases available for this purpose are carbon monoxide, cyanogen, and gaseous hydrocarbons. Of these, carbon monoxide and cyanogen bearing gases are the most effective, but the former gives a much more uniform gradation of the carbon content from the exterior to the interior of the case, and is to be preferred on that account. The reaction by which carbonization is effected with carbon monoxide is generally assumed to be the following: $2\,CO+3Fe=Fe_3C+CO_2$.

Carbonizing Materials: A great number of different carbonizing materials, consisting of gases, liquids and solids, have been tested by the many investigators, and of these, solids are by far the most convenient for the purpose as well as the most effective, when they are of the proper composition. In the use of solid carbonizers, the chief essentials to success are carbon in suitable form, a sufficiently high and properly regulated temperature maintained for a proper length of time, and reasonable care as to the details of preparing the carbonizer and packing the articles therein. For supplying the carbon, many different substances may be employed, such as coke, wood charcoal, sugar charcoal, animal charcoal, charred bones, charred leather, etc. Coke and wood charcoal are not as rapid as these other forms of carbon. Care is required in using coke, bones, leather and animal charcoal to guard against imparting phosphorus and sulphur to the metal. The material selected should be ground or crushed to the proper degree of fineness and to a fairly uniform size, after which it should be sifted free of dust.

Packing and the Action of Charcoal Carbonizer: Assuming that charcoal is selected, the article or articles to be case hardened are packed with the carbonizer in a hardening pot or box of suitable size and shape. The boxes may be of soft steel, wrought iron or cast iron. The walls should be thin, about one-fourth inch in thickness, and of a size and shape that will

permit the rapid penetration of the heat, so that the lag in temperature of the central part of the packed box behind the furnace temperature will be as small as possible. The best shape is one that conforms to that of the piece or pieces to be carbonized. The article, or each of the articles, in a charge should be placed so that it will be completely surrounded by a layer of the carbonizing material, about an inch in thickness. In case it is desired to carbonize only certain parts of the article, the parts that are not to be carbonized may be covered with asbestos cement, or slaked lime or fire clay in the form of a paste. When the packing has been completed, the open end of the box is closed with a neatly fitting lid, which is pressed down firmly against the top layer of carbonizing material and fastened tightly in place, so that it will permit no displacement of the pack or packing in handling. The small opening about the edge of the lid is then luted with asbestos cement, clay, or a mixture of fire clay and sand; then, the box is ready for charging. When the contents of the box have reached a certain temperature in the furnace, the oxygen of the air that fills the interstitial spaces of the packing reacts with the carbon, giving carbon monoxide, which in turn reacts with iron to give iron carbide and carbon dioxide gas, as previously stated. The iron carbide, of course, remains in the metal to form the case, while the carbon dioxide is given off. When it comes in contact with the carbonizing material, CO gas is again generated, thus, $CO_2+C=2\,CO$. This CO then reacts with iron as before. This cycle is made again and again, until the process is stopped, or the iron becomes saturated with carbon. In the case of bones, leather, and other animal or vegetable matter, other more complicated reactions, due to cyanogen and hydrocarbon vapors given off by these substances, occur in addition to the simple reactions resulting from the carbon, as explained in connection with the use of charcoal.

Carbonizing Mixtures and Compounds: These simple substances may also be used as the base materials for various carbonizing mixtures designed to suit the conditions and the results desired. Thus, in the case of thin cases, where it is desired to increase the speed or rate of penetration and where the forming of a case of uniform thickness is essential, the following mixtures have been recommended:

1. Powdered wood charcoal with a little heavy hydrocarbon oil added.

2. Powdered wood charcoal, leather charcoal, and lampblack in the proportion of 5, 2, and 3 parts, respectively.

3. Powdered wood charcoal, 7 parts, and animal charcoal, 3 parts.

4. Powdered wood charcoal, charred horn and animal charcoal, in proportion of three parts of the first and two parts of each of the others.

The increased rate of carbonization that may be obtained by the use of these mixtures is due to the fact that they give off volatile hydrocarbons and cyanogen compounds as well as carbon monoxide, and that these compounds are capable of causing carbonizing reactions independent of and in addition to that involving carbon monoxide.

In addition to these, mixtures of wood charcoal with common salt or with barium carbonate have been found very efficient and desirable carbonizing materials. Just what part common salt may play in the process is not known, but the action of barium carbonate is easily explained. At the higher carbonizing temperatures it is decomposed according to the following reaction: $BaCO_3 = BaO + CO_2$. The CO_2 thus generated is immediately reduced by the hot carbon to CO gas, each volume of CO_2 giving two volumes of CO; thus, $CO_2 + C = 2\ CO$. The net effect of the barium carbonate, then, is to increase materially the amount of the CO available. By exposing the mixture, after use, to the air, the barium oxide takes up CO_2, forming barium carbonate again, so that with the occasional addition of small amounts of charcoal the same mixture may be used repeatedly. Another advantage secured in using the barium carbonate-charcoal mixtures is that the danger of contaminating the steel with sulphur is entirely avoided, as these materials may be obtained practically sulphur free. The mixture that has been found to give the best results is one composed of 40 parts of the carbonate to 60 parts of charcoal by weight.

Quick Acting Carbonizers: When it is desired to obtain a thin case of high carbon content in a very short interval of time, quick acting mixtures are used. The substances employed in these mixtures are wood charcoal, bituminous coal, sawdust, charred leather, prussiate of potash, sal soda and common salt. From these substances mixtures that will give various speeds of carbonizing may be made. For example, a mixture of 2 parts wood charcoal, 1 part salt, and 3 parts sawdust is relatively slow in its action while a mixture of 10 parts charred leather, 2 parts prussiate of potash and 10 parts sawdust is characterized as very rapid.

Heating the Carbonizing Pack: For heating up the charged carbonizing boxes, some form of gas fired muffle furnace is preferable. The essential requirements of the furnace are that it must be capable of giving a maximum temperature of at least 1000° C. (1832° F.), any definite temperature lower than 1000° C. (1832° F.), and also be capable of maintaining these definite temperatures uniformly throughout the heating chamber for periods of several days at a time. In order to avoid the rapid oxidation and consequent destruction of the carbonizing boxes, a reducing atmosphere should be maintained in the heating chamber, and furnaces constructed so as to effect this result are most desirable. The furnace should be cold, or nearly so, when the packed boxes are charged, and the heating, up to the carbonizing point, should be very gradual. The steel will thus have time to adjust itself to the conditions; the pack will be uniformly heated throughout, so that carbonization will begin in all parts of the pack at the same time; and the evolution and generation of gases, which begins at temperatures slightly below 700° C., will not be too energetic. The temperature and the length of time for carbonizing depend on the depth and the carbon content of the case desired, the

carbonizing material, and the character of the raw iron or steel. In general, for a given set of materials, the higher the temperature and the longer the time of carbonizing, the greater will be the depth of the carbonized zone; and when solid carbonizers are used, the same may be said with respect to the maximum carbon content or carbon concentration of the case. That the carbonizing material may affect the speed of the carbonization has already been intimated in discussing carbonizing mixtures. A similar difference is also found in their action with respect to the concentration of the carbon. Thus, while one carbonizer will give, for example, a case with a surface hardness corresponding to .80 per cent. carbon at 870° C., 1.05 per cent. carbon at 900° C., etc., another will give only a .70-per cent. case at 870° C. and a .90-per cent. case at 900° C. In treating ordinary carbon steel, a temperature between 875° and 900° C. (1600° to 1650° F.) is considered best to avoid large grain size and obtain the most satisfactory results. With this temperature determined upon, the depth of the case and the concentration of the carbon may be regulated by varying the time of carbonizing and the composition of the carbonizing material employed.

Controlling the Temperature: In regulating the temperature of the pack it should be kept in mind that the temperature of the furnace cannot be relied upon to give the actual temperature of the interior of the pack. The temperature of the latter, during the time it is being brought to heat, will tend to lag behind that of the furnace, and after a temperature of 700° C. (1292° F.) is passed the chemical reactions within the pack itself may result in the liberation or absorption of a quantity of heat sufficient to maintain its temperature several degrees above or below that of the furnace. Evidently, then, some means of ascertaining the temperature of the interior of the pack is very desirable. For this purpose a pyrometer of the thermo-electric type is admirably suited, because with this instrument the hot junction of the thermo couple may be placed in the center of the pack as it is being made up, or inserted through a small tube so placed.

Removal of the Articles from the Boxes After Carbonizing: In cases where it is desired to prevent the oxidation of the surface of the articles treated, it is necessary either to permit them to cool nearly to atmospheric temperature in the boxes or to quench them by emptying the entire contents of the box, inverted and with its opening very close to the surface, into the quenching liquid. Some materials are quenched from the carbonizing temperature for the purpose of hardening them, but in order to refine the grain, which is coarse, due to the long period of exposure to a relatively high temperature, and secure the greatest toughness combined with greatest hardness, the carbonized articles must be subjected to special heat treating processes, in which case the articles may be removed from the carbonizing boxes at any convenient time and allowed to cool in the air to atmospheric temperatures or at least to a temperature that gives a black color.

Heat Treatment of Case Hardened Articles: The correct heat treatment of case hardened articles involves a combination of methods suitable to steels of different carbon content. Upon the core of low carbon content there is superimposed a layer of high carbon steel, which may be of hypo-eutectoid, eutectoid, or hyper-eutectoid composition, and the treatments should be varied to correspond to these three different cases and to the temperature at which the carbonization was carried on. To secure maximum refinement of grain in the core it is necessary to heat the steel just above its Ac_3 point, which for a .15-per cent. to .20-per cent. carbon core, is a temperature near 900° C. (1652° F.), and quench, preferably, in oil. As this temperature is far above the Ac range of either a hypo-eutectoid or eutectoid case, this treatment hardens the case but leaves its grain structure relatively coarse. Therefore, the article should be reheated to a temperature slightly above the $Ac_{3\text{-}2\text{-}1}$ range of the case and again quenched in water or oil. Finally, to prevent brittleness in the case and to remove strains, it is desirable to temper the steel at once by reheating to 200° C. (492° F.) or over, depending upon the hardness it is desired the case shall retain. The temperature mentioned would relieve stresses but would reduce the hardness very little, if any. Hyper-eutectoid cases require that the treatment described above be modified to the extent that either the first reheating shall be above the Ac_{cm} range, or that the article be quenched from the carbonizing temperature, in order that the excess cementite may be retained in solution. The further treatment may then be a repetition of that for hypo-eutectoid cases, or merely a quenching from above the $Ac_{3\text{-}2\text{-}1}$ range (750° C.). This last method leaves the core somewhat brittle, due to a large grain size, but produces a surface of exceptional wear resisting properties. In any of these cases, where the carbonizing has been carried on at a high temperature and has occupied a considerable period of time, double quenchings are sometimes necessary to secure the best results.

Superficial Hardening: For the most superficial hardening and at the same time the most rapid, such as is sometimes desirable for hardening certain tools, cyanide of potassium or prussiate of potassium alone may be used in either one of two ways. In one, the salt is melted and the article to be hardened is brought to the quenching temperature by immersing it in the fused salt, held at that temperature for a few minutes, the exact time depending upon the amount or extent of the carbonization desired, and then quenched as for ordinary hardening, except that lime water should be used to neutralize the poisonous cyanide. In the other method, the article to be hardened is heated to the hardening temperature and is then sprinkled with the dry salt or plunged into a quantity of the dry salt. It is then reheated to the hardening temperature and quenched, as in the first method. Although often spoken of as such, this treatment is not a true case hardening process.

CHAPTER III.

CONSTITUENT ELEMENTS OF COMMERCIAL CARBON STEEL AND THEIR INFLUENCE UPON ITS MECHANICAL PROPERTIES.

Introductory: Needless to say that a complete discussion of the effects upon the properties of steel of all the elements that naturally may be found in it or that may be added to it would be a very lengthy one, indeed. Even a thorough study of the subject as limited by the title of this chapter would involve an immense amount of labor on the part of the writer and much time on the part of the reader to peruse it. The most that is to be expected, therefore, in the following discourse is but a brief summary of the opinions of the different authorities as presented in the various text books, the trade papers, and the reports of conventions, and some deductions and conclusions arrived at through personal experience. In examining the information from these sources, the student is confronted with much difference of opinion, which often results in much confusion of thought. But a systematic search enables the student to arrive at the conclusion that certain elements, like manganese, for example, are beneficial; others, like oxygen, are harmful; some, like phosphorus and sulphur, are of doubtful influence; while others may be beneficial or harmful, depending upon conditions. In this regard, it is important to note that opinion at present is changing with respect to the influence of many of the elements. This is particularly true of phosphorus and sulphur, both of which were recently held to be injurious to steel under any conditions and at all times. Now, however, these elements, far from being considered as foes to good steel making, are within certain limits, being looked upon as harmless to the steel, and even as aids for certain purposes. With these things in mind, an attempt has been made here to put down what appears to be the truth concerning these elements as revealed after a study such as that suggested above.

Properties of Iron: Since iron is the element that forms the base material for the steel, the discussion of this subject is naturally begun with a consideration of the properties of this element, though pure iron is practically unknown commercially. As the physical and chemical properties of the element will be found under the subjects of Physics and Chemistry and the Heat Treatment of Carbon Steel, it is not necessary even to tabulate them here. In this connection, special emphasis is to be laid upon the strength and ductility of the element, but it is difficult

to decide what the true values of these properties are. Pure iron can now be produced by electrolytic processes in fairly large quantities, and the testing of it would appear to be a very simple matter, but the results reported by investigators are found to vary widely. This variation in results may be attributed to differences in methods of preparing the specimens for testing. The mechanical properties of pure iron, like those of other metals, depend mainly upon the grain size and form, which in turn is affected by the mechanical working and the heat treatment it receives. If, after working, the piece be annealed or normalized, for example, the temperature must be raised to almost 1000° C. (1800° F.) and the effect of such a high temperature in producing grain growth is very marked. Furthermore, the treatment may result in the absorption of small amounts of gaseous impurities such as nitrogen, oxygen, and hydrogen, which would be capable of modifying its properties to some extent. In addition, the size of the section will affect the ductility results. Thus, reports of pulling tests on normalized and annealed specimens of electrolytic iron show results varying as follows: Tensile strength, 36,000 to 41,000 pounds per sq. in.; yield point, 16,000 to 21,000 pounds per sq. in.; elongation in 2 in., 25 per cent. to 50 per cent.; in 8 in., 30 to 40 per cent.; and reduction of area, 60 per cent. to 80 per cent. These results are no more satisfactory than those formerly obtained by calculation from pulling tests on the purest forms of wrought iron, ingot iron, and dead soft steels. A careful survey of many results obtained by both methods indicate that pure iron, slowly cooled after hot working and tested in masses large enough to compare with the ordinary soft steel test piece, would give a tensile strength of about 39,000 pounds per sq. in.; a yield point of about 20,000 pounds per sq. in.; an elongation in 8 in. of about 30 per cent.; and a reduction of area of nearly 80 per cent.

Effect of Carbon: The influence of carbon upon iron is so characteristic and beneficial that it is employed as the controlling element in regulating the physical properties of all common steels. While this element is capable of changing most of the physical properties of iron by uniting and alloying with it, its most important influence is connected with the hardness, strength, and ductility of the metal. Its effect upon these properties may be varied in extent by heat treatment, as is fully explained in the chapter on that subject. It is to be noted here, however, that, with respect to its influence upon the strength and ductility of naturally cooled steel, the average results obtained by four eminent investigators show that for each 0.1 per cent. carbon added to steel up to .90 per cent., these properties are affected approximately as follows:

Yield point is raised.....3987 pounds per sq. in.
Maximum stress is raised.....9363 " " "
Elongation is reduced.....4.33%
Reduction of area is reduced.....7.27%

Above 1.00 per cent. in carbon content, the brittleness of steel increases so rapidly, due to the presence of excess cementite, that its use is then limited to articles, relatively few in number, requiring great hardness and little toughness or ductility. Hence, the carbon content of commercial steel will seldom exceed 1.10 per cent.

Influence of Manganese: The chemical properties of manganese, which impart to it the power of combining with the oxygen of ferrous-oxide and of setting free the iron, make it invaluable as a cleansing, or deoxidizing agent, and have been referred to, time and again, in describing the various processes of making steel. It is here appropriate to consider the effect of the manganese that remains in the steel after deoxidizing. Of this residual manganese, it may be said that every one is agreed that its effects, when present up to certain limits, varying with conditions and the use to which the steel is to be put, are wholly beneficial. Aside from causing the steel to roll and forge better, it is a well known fact that manganese adds somewhat to the tensile strength, this beneficial effect depending upon the carbon content as well as that of the manganese. According to H H. Campbell[1] the tensile strength of untreated open hearth steel, containing .30 per cent. manganese and over, rises for each increase of .01 per cent. in manganese and with the carbon content as shown in the following table:

Table 71. The Effect of Manganese Upon the Tensile Strength of Steel.

Each increase of .01% Mn. above .30% or .40% raises the tensile strength in:

Carbon Content	Basic Open Hearth (Mn. Above .30%)	Acid Open Hearth, (Mn. Above .40%)
.05	110 lbs.	.....
.10	130 "	80 lbs.
.15	150 "	120 "
.20	170 "	160 "
.25	190 "	200 "
.30	210 "	240 "
.35	230 "	280 "
.40	250 "	320 "

When the manganese content is less than .30 per cent., this law of increase is disturbed by other influences of an unknown character, which may even cause a complete reversal of tendencies and the tensile strength to rise when the content falls below .30 per cent. Above 1.00 per cent., manganese begins to produce hardness and brittleness, which tendency becomes very marked as the content reaches and passes 3.00 per cent. Like the tenacity, these properties are similarly affected by the relation of the manganese to the carbon content. Plain carbon steels, therefore, seldom contain more than 1.00 per cent. manganese, and those commercial

[1]See Manufacture and Properties of Iron and Steel. Published by McGraw Hill Book Co.

steels containing from 1.00 to 2.50 per cent. manganese are to be considered alloy or special steels.

Influence of Manganese in Heat Treatment: Relative to heat treatment, the effect of manganese upon the heat treating qualities of the steel are not to be overlooked. In the case of ordinary open hearth steels, this brittleness of the high manganese steels is associated with the tendency of such steels to crack just after or during the quenching. Much care, therefore, must be exercised in selecting steel for heat treatment to secure the proper proportion of carbon and manganese, for which purpose the following statements will be found to apply in a general way:

1. Steels containing 1.00 to 2.50 per cent. manganese should not be quenched in water, whatever their carbon content may be, but with the per cent. of carbon no higher than .60 they may, depending on the design of the body and the condition of the steel, be quenched in oil.

2. Steels containing about 1.00 per cent. manganese, if of low or medium carbon content, may be quenched in water, though the risk of cracking is still great.

3. A manganese content of .40 per cent. or less is preferable in high carbon steels near the eutectoid (.90% C.) composition, when such steels are to be hardened by quenching in water.

4. In hyper-eutectoid steels, such as high carbon tool steels, the manganese content should not rise above .25 per cent.

5. Each 0.1 per cent. of manganese lowers the critical range on heating by about 3° C.

6. According to one authority, electric steel permits a higher content of both the carbon and the manganese in heat treating than would be permissible with ordinary open hearth steel.

Influence of Manganese on Sulphur: Another great benefit to be gained from the use of manganese is due to its ability to neutralize, or offset, the evil effects of sulphur. Like oxygen, this element combines with both iron and manganese to form sulphides, but in the presence of both elements and at a high temperature it unites with the latter in preference to the former, thus producing manganese sulphide, MnS, which is practically harmless in steel for reasons that will be explained shortly.

Influence of Sulphur: The effect of this element upon the tenacity and ductility of steel, at least up to 0.1 per cent., is so slight that it may be disregarded. One investigator asserts that it accelerates corrosion of the steel that contains it. Its most marked effects, however, are encountered in hot working, i. e., rolling or forging, the steel, and they were formerly believed to be always evil ones. That in the form of ferrous sulphide, FeS, it is capable of doing great harm in steel by causing red-shortness is conceded by all, but when neutralized with manganese in sufficient amount it may be comparatively harmless, even when present to the extent of a somewhat higher content than one-tenth per cent.

Why Manganese Neutralizes the Effect of Sulphur: The only plausible explanation so far offered to account for the difference in the effect of the two sulphides is that the iron sulphide forms films, or cell walls, about the grains of the metal, and as this sulphide fuses at a red heat, these cell walls, by becoming fluid, interrupt the continuity of the mass and so render the steel hot short. Manganese sulphide, instead of forming envelopes about the grains of the metal, collects, or segregates, into globules at temperatures near that of the metal on solidifying, upon which the main body of metal then contracts. Manganese sulphide has a much higher fusion point than ferrous sulphide, hence does not melt at a rolling heat, but becomes merely plastic like the rest of the metal. In this form, it is rolled into fibers, which give to the steel, when present in sufficiently large quantities, a fibrous structure similar to that of wrought iron. In order to get the full benefit of the manganese, it is necessary that it should be present in the steel to the extent of about three times the theoretical amount required for the formation of the sulphide. Roughly, this means that the per cent. of manganese should be five times that of the sulphur.

Uses for Sulphur in Steel: This fibrous structure of high sulphur steel is made use of in the manufacture of free cutting steel, like screw stock, for example, because the free cutting properties of this steel are undoubtedly due to its fibrous structure. Thus, in this case, at least, sulphur is to be regarded as a friend rather than as a foe. In this connection, it should be observed that experiments conducted during 1914 and 1915 in both this country and England tend to show that sulphur, when accompanied with a sufficient amount of manganese, is not such an enemy as it is sometimes supposed to be. Extensive investigations by our own research department have shown that there is practically no difference in the rolling, forging or welding qualities, nor in the physical properties of steels containing from .030 per cent. to .120 per cent. sulphur. It is interesting to consider how the unfavorable attitude toward sulphur came about. Up to within the present decade, most of the steel produced in this country was made by the acid Bessemer process in which the sulphur content would often range from .070 per cent. to .100 per cent. Yet there was no complaint about this steel; and that it gave excellent service for nearly all purposes that steel is used cannot be denied. But with the advent of basic steel, the notion became prevalent, through academic discussions to explain why this steel should be better than Bessemer, that even a small quantity of sulphur was harmful to the steel. This argument was doubtless based on the fact that in crucible steel, which usually carried a low content of manganese, the harmful effects of sulphur are very noticeable. As a result of this agitation, consumers naturally insisted on placing the limit for sulphur at the lowest possible figure, under .040 per cent. or even under .030 per cent., in order to secure the better steel. Evidently, however, such an attitude should be corrected now, for economic reasons, if no other. In view of the fact that it is becoming increasingly difficult

to keep the sulphur content below .040 per cent., it seems ridiculous to insist upon so low a limit, when the evidence points so strongly to .100 per cent. as a limit that may be made to serve as well, for many purposes, at least. As most basic steel made in this country appears to tend naturally toward a sulphur content of from .050 per cent. to .060 per cent., even raising the limit to .060 per cent. would result in a great saving.

Influence of Phosphorus: Phosphorus is another element that has been painted a little blacker, perhaps, than it should. It has been everywhere charged with producing cold shortness, or brittleness when cold, but experiments and tests conducted by our research department, during the first half of the year 1917, seem to indicate that up to .10 per cent. at least, phosphorus does not produce brittleness in the metal to a degree that is noticeably harmful. In these experiments, steels with phosphorus contents ranging from .018 per cent. to .110 per cent. were subjected to severe cold bending, stamping and pressing tests, like those steel is called upon to withstand in shaping, with the result that the higher phosphorus steels stood up under the tests as well as the low phosphorus grades, otherwise of identical composition. That it does increase the hardness and tensile strength of the steel, causing at the same time a proportionate reduction in the ductility, is well established as a fact. In this respect it is very similar to carbon. Some authorities claim that it increases the tensile strength a little more than carbon with a less reduction in the ductility; others say that its effect is practically the same as carbon except that it increases the brittleness a little more. Campbell claims that the tensile strength of basic steel is increased 1000 pounds for each increase of .01 per cent. of phosphorus. It, also, benefits the wearing properties of the steel in much the same way that carbon does. In low carbon steels, it is used in many cases with entirely beneficial results. Thus, it is useful in sheet bar, as it is claimed that it prevents the sheets from sticking together in the pack during the rolling and is beneficial in other ways, also.

The Two Evils of Phosphorus: However, it is not to be inferred that the indiscriminate use of high phosphorus steel is advocated, because it has, according to Howe, Harbord and others, at least two evil tendencies that make it a dangerous element in steels for certain purposes. Speaking of these tendencies, Harbord states that, of all the impurities usually present in steel, practical experience has established the fact that phosphorus is the one that most prejudicially influences the physical properties of the metal by producing brittleness under shock, and hence for practical commercial purposes, phosphorus in steel should not exceed .080 per cent. Again, Howe maintains that while phosphorus sometimes affects iron but slightly, at other times, under apparently similar conditions, it affects it profoundly. In view of this fact, which may be called the treacherousness of phosphoretic steel, it is difficult to define a limit for the maximum content of phosphorus which can be safely allowed in steel, but reasoning that the lower this is,

the safer the material, many would insist upon a very low limit. That this limit may be unreasonably low is illustrated in the case of structural steel. Many users of this material refuse to accept any steel that contains a higher percentage of this element than .04 per cent. Yet a class of material subjected to much more severe usage in service, namely, railroad rails made by the Bessemer process, is permitted to contain as much as .110 per cent. phosphorus. Furthermore, while structural material is subjected to static stresses mainly, a class of stress that phosphoretic steel is most capable of resisting, rails are required to withstand shocks and impacts, which the evidence shows, high phosphorus steels should be least capable of resisting.

Influence of Silicon: Apparently owing to the fact that all but traces of silicon may be removed in any and all of the processes for manufacturing steel, the attention of investigators has not been so universally directed to the effects of this element on steel as in the case of the other impurities. Besides, whatever evidence may be collected will be found to vary somewhat. Thus, while certain English investigators found that steels containing as much as 2.00 per cent. silicon, a content much higher than any employed in ordinary carbon steel, suffered a marked reduction in ductility, others maintained that the ductility is not markedly affected up to a content of .70 per cent. All agreed that the tensile strength is increased, and some maintain that small percentages of silicon increased the resistance of the steel to shock. In short, it is generally accepted by all practical steel men that silicon up to .75 per cent. is beneficial, that it increases the yield point and tensile strength but does not materially impair the ductility. This statement is in accord with the experience of our own Company, who found, for example, that in a certain specification calling for a tensile strength of 80,000 pounds with an elongation of 20 per cent. in eight inches, requirements that cannot be approached in plain untreated carbon steel, very satisfactory results were obtained by the addition of .50 per cent. silicon. Like manganese, silicon is a wonderful deoxidizer, or cleanser, of steel, and it is possible that the improvement in the quality of steel, and of basic steel in particular, which the addition of small quantities of the element produce, is due rather to this property than to any influence the residual silicon in the steel may have. Acid open hearth steel probably owes whatever superiority it has over basic steel to this action of silicon in the bath. In acid practice a slight rise in the silicon content of the metal is taken as a sure indication that the bath is thoroughly deoxidized. Spring steel with the silicon ranging from .25 per cent. to .35 per cent. has greater resiliency than steels of lower silicon content, and without increased brittleness. In steel castings it is especially beneficial, as it tends to prevent blow holes and thus promotes soundness. In steels intended to be case hardened, silicon is an objectionable element, as it retards the absorption of carbon. Therefore, in such steels the silicon content should be low, as the retarding effect begins at about .04 per cent.

In sheet bar, silicon is like phosphorus in that it tends to prevent the sheets in a pack from sticking together. For this purpose .06 per cent. is sufficient.

The Influence of Oxygen in steel has been thoroughly discussed and emphasized in connection with the various methods for manufacturing steel. It may, however, again be pointed out that its effects are all evil ones, causing both red shortness and cold shortness in steel, and that when present even in so small amounts as .03 per cent. it shows a marked tendency to produce brittleness under shock. The amount of oxygen steel is capable of retaining is small. That retained even by over-blown Bessemer steel without deoxidizing is less than .15 per cent.

Combined Effect of the Elements on Tensile Strength of Steel: These elements, iron, carbon, manganese, sulphur, phosphorus, silicon and oxygen, are the ones found in all commercial grades of steel. Having discussed their effects separately, it may now be advantageous to consider their combined effect upon the metal. Of these elements only oxygen is to be looked upon as being always an enemy. The influence of manganese in steels that are not to be heat treated is always good, as is also that of silicon in small amounts. The tensile strength is raised by carbon, manganese, phosphorus, and silicon, while the ductility is decreased by carbon, manganese, and phosphorus. According to H. H. Campbell the influence of these elements varies in the different kinds of steels; and for the two kinds of open hearth steels in their natural state, that is, without any heat treatment, he sums up the combined effect of carbon, phosphorus and manganese on the tensile strength to be approximately as given in the following formulas:

First Method (of Least Squares):

A. Acid Steel 38600+1210 C+890 P+R=Ultimate Strength.

B. Basic Steel 37430+950 C+85 Mn+1050 P+R=Ultimate Strength.

Second Method (by Plotting):

C. Acid Steel 40000+1000 C+1000 P+X Mn+R=Ultimate Strength.

D. Basic Steel 41500+770 C+1000 P+Y Mn+R=Ultimate Strength.

In these formulas 38600, 37430, 40000 and 41500 represents the initial strength of pure iron; C, P, Mn, stand for carbon, phosphorus and manganese expressed in hundredths of one per cent., respectively; X and Y represent variables changing with the carbon content as given under the heading, Influence of Manganese; and R is a factor that depends on the finishing temperature, and may be either plus or minus.

For low carbon plain basic steel, such as that used for plates and structural shapes, rolled at the ordinary temperature for hot rolling, the following simple formula is used by many inspectors:

T (Ultimate Strength)=39000+950 C+1050 P+85 Mn.

The symbols in this formula have the same significance as the same symbols in Campbell's formulas.

The Influence of Copper upon the mechanical properties of steel, when present in small amounts, say up to .50 per cent., is not very pronounced. In terms of tenths of one per cent., the effect of copper as determined by several different investigators is about as follows: The yield point is increased 1800 pounds in steels of low carbon, and 720 pounds in those of medium carbon content; the maximum stress, or ultimate strength, is increased 1200 pounds for low carbon, and 600 pounds for medium; the elongation is decreased .75 per cent. for low carbon, and .25 per cent. for medium; the reduction of area is decreased .45 per cent. for low carbon, and .50 per cent. for medium. From these results it is to be decided that the effect of small percentages of copper is slight, and what effect it has is beneficial. This declaration agrees, also, with the verdict of the American Society for Testing Materials. For years copper was looked upon as being very injurious to the steel, it being charged with making the steel red-short and unweldable. However, as early as 1899, A. L. Colby made an extensive series of investigations to determine what really were the effects of small percentages of copper upon the physical properties of the steel. Briefly, these investigations and the results obtained were as follows: A steel shaft 15 inches in diameter by fourteen feet long, corresponding in composition with the propeller shafts adopted by the U. S. Navy Board, but containing also .565 per cent. of copper, was forged without difficulty. Test specimens were doubled flat in the cold without showing cracks or flaws, and the tensile strength and ductility were well up to requirements of the Navy. In another series of tests the material, containing .553 per cent. copper, was forged into a gun-tube, and satisfied all the requirements for the U. S. Navy for a 6-inch gun. Mild steel in the form of ship-plates, containing .573 per cent. copper, passed all the tests required, except a quarter-inch plate which was rolled too cold. The bending and quenching tests of the bars cut longitudinally were also satisfactory, but some, bent transversely to the direction of rolling, developed cracks. The material could be successfully welded, only one of the specimens tested breaking at the weld, and even then the breaking load was 61,630 pounds per square inch. Flanged cold, the material gave excellent results, and though most severely tested, developed neither defects nor flaws. Other investigations were directed to merchant bars, rails, and nickel steel all containing copper, and in no case was there any evidence of red-shortness, although the copper ranged from .089 per cent. to .486 per cent. Colby's conclusions were that a good steel may contain as much as 1 per cent. of copper without suffering, provided that the sulphur content is not also high, in which case the metal is likely to crack in rolling.

Even small amounts of copper in steel causes the latter to resist corrosion by acids much better than steels that do not contain it. The research department of the American Sheet and Tin Plate Company has shown that .15 per cent. to .25 per cent. of copper in steel sheets of heavy gauge practically preserves them from general corrosion, and that the

resistance to corrosion begins to be manifested by the steel with the copper content as low as .03 per cent. While copper compounds occur in many iron ores, only traces, if any, are to be found in the Lake Superior ores. Hence steels made from these ores are practically copper free, except in cases where it is added to produce the non corroding steels. Occasionally, however, whether introduced through accident or from the ore, steels will be found to contain copper to the small amount of .01 per cent. to .02 per cent.

Influence of Tin: While this element is not found in any of the iron ores, the use of detinned scrap may result in its introduction into the steel during the process of manufacture. Hence, the effects of small quantities of tin in steel are not to be overlooked, but unfortunately this matter does not appear to have been very thoroughly investigated. What work has been done shows that tin forms an alloy or a compound with iron, which has the property of making the steel very hard at rolling temperature. Thus, at one steel works it was impossible to roll a heat of steel into which there had accidently been introduced tin to the extent of .75 per cent. Tin in steel increases the yield point and the ultimate strength of the metal, but to a less degree than carbon or phosphorus. So far as they have gone, investigations appear to indicate that .05 per cent. tin in steel would have little influence upon its mechanical or physical properties, but that larger quantities must be avoided.

Influence of Arsenic: This element does not occur in any of the iron ores from the Lake Superior region, and is, therefore, never found in steels made from these ores. When present, however, in small amounts, unless special precautions are taken in making an analysis of the steel, it is reported as phosphorus. Small amounts of arsenic do not affect the physical properties of steel; above .20 per cent. its effect is similar to that of phosphorus, causing cold shortness.

CHAPTER IV.

STRUCTURAL ALLOY STEELS.

SECTION I.

INTRODUCTORY.

Definitions: So many different elements may occur naturally in steel, or be added to it, in such varying amounts with corresponding variations in effects, that it is a difficult matter to determine just what constitutes an alloy steel even from the standpoint of chemical composition alone. When it is further considered that the different methods of manufacture also exert their influence, and that certain elements may be added or allowed to remain for widely different reasons, the difficulty of wording concisely an adequate definition becomes more apparent. The definition adopted by the International Association for Testing Materials is as follows: "Alloy steel is steel which owes its distinctive properties chiefly to some element or elements other than carbon, or jointly to such other elements and carbon. Some of the alloy steels necessarily contain an important percentage of carbon, even as much as 1.25 per cent. There is no agreement as to where the line between alloy steel and carbon steel shall be drawn." In this connection it is well to note that elements other than carbon are always to be desired in steel of commercial grade, at least. Such elements may be added or permitted to remain for three distinct reasons, namely, (1) to correct or prevent defects that otherwise would be liable to occur in the final product; (2) to impart to the steel some distinctive property or to improve materially its natural properties; (3) to form alloys for the purpose of experimentation and investigation. The addition of silicon and manganese to steel illustrates the point it is desired to explain. In ordinary practice small amounts of these elements are added to deoxidize the steel, and incidentally the small amounts that remain in the metal may improve its properties. Large amounts of these elements, 1.50 per cent. to 4.50 per cent. in the case of silicon, and 11 per cent. to 14 per cent. in the case of manganese, may be added to impart properties to the steel that are distinctive and useful. Other proportions may be used, of course, which result in imparting properties that, while they may be distinctive, are not useful, and so these iron alloys have only a scientific value. With these facts in mind, we agree with Henry D. Hibbard, who suggested the following definitions:

[1]See Manufacture and Uses of Alloy Steels, Bureau of Mines Bulletin 100

"**Simple steel,** which is often called carbon steel (or plain steel), consists chiefly of iron, carbon, and manganese. Other elements are always present, but are not essential to the formation of the steel, and the content of carbon or manganese, or both, may be very small."

"**Alloy steel** is steel that contains one or more elements other than carbon in sufficient proportion to modify or improve substantially and positively some of its useful properties." These steels, since they contain a special element, are sometimes called special steels.

"**Alloy-treated steel** is simple steel to which one or more alloying elements have been added for curative purposes, but in which the excess of the element or elements is not enough to make it an alloy steel."

All the alloy steels manufactured by The Carnegie Steel Co. are made either in the open hearth or the electric furnace, and the alloying elements chiefly employed are nickel, chromium and vanadium. While a large tonnage of steel, containing slightly higher percentages of copper, silicon or manganese than that prescribed by ordinary practice for carbon steels, is made, these elements in such small quantities are not to be considered as alloys but rather as curative or intensifying elements. A definition that would agree with the customs of this company, then, would appear to be the following: An alloy steel is steel, made by the open-hearth or the electric process, which contains, in addition to carbon, some element or elements added with the object of modifying and substantially improving its mechanical properties in such a way as to make it more suitable for the purpose for which it is intended. This definition does not include the addition of copper for obtaining non-corrosive steel, a chemical property, nor the addition of small amounts of phosphorus to basic steel for sheet bar, nor the sulphur in screw stock, nor manganese and silicon added for curative purposes.

Carnegie Types and Grades: To illustrate the importance of the elements mentioned above as being the ones chiefly employed in alloy steels, the types and grades of commercial alloy steels manufactured by the open-hearth process and fixed in 1922 as standards by the Carnegie Steel Company may be cited. They are shown in table 72, next page. These types and grades are subject to change, of course, and, except from the standpoint of tonnage, represent only a small part of the whole field of alloy steels. They are, however, representative of the steels made from the three alloying elements that, up to the present time, have been found to be of greatest value commercially, namely, nickel, chromium, and vanadium. The elements next in importance in the production of structural alloy steels are molybdenum, manganese, and silicon, all of which have been employed to make steel that was substituted for some of the types given in the table, or for carbon steel, in the construction of certain parts of automobiles and other machines. None of the types of steel produced

by the last three elements, however, have been in use long enough or extensively enough, to justify an attempt to establish any standards of composition for the various types.

Table 72. Carnegie Standard Open Hearth Alloy Steels.

Nickel Steel.		Low Nickel-Chrome Steel.	
Carbon	.10 to .20, .15 to .55%	Carbon	.10 to .25, .20 to .55%
Manganese	.30 to .60, .50 to .80	Manganese	.30 to .60, .50 to .80
Phosphorus not over	.04	Phosphorus not over	.04
Sulphur not over	.045	Sulphur not over	.045
Nickel	3.25 to 3.75	Nickel	1.00 to 1.50
		Chromium	.45 to .75

Chrome Steel.		Chrome-Vanadium Steel.	
Carbon	.15 to .45, .35 to .55	Carbon	.15 to .55
Manganese	.30 to .60, .50 to .80	Manganese	.50 to .80
Phosphorus not over	.04	Phosphorus not over	.04
Sulphur not over	.045	Sulphur not over	.04
Chromium	.60 to .90, .80 to 1.10	Chromium	.80 to 1.10
		Vanadium not under	.15

Chrome-Vanadium Spring Steel.		Special Low Chrome Spring Steel.	
Carbon	.40 to .55%	Carbon	.80 to .95%
Manganese	.80 to 1.00	Manganese	.30 to .50
Phosphorus not over	.04	Phosphorus not over	.04
Sulphur not over	.05	Sulphur not over	.05
Silicon not over	.20	Silicon not over	.20
Chromium	1.00 to 1.25	Chromium	.20 to .40
Vanadium not under	.15		

SECTION II.

NICKEL STEEL.

Manufacture of Simple Nickel Steel: Nickel steel, said to have been used for the first time in 1888, may be made by any of the various processes for the manufacture of steel, but the greater portion is produced by the open-hearth process. At the steel-melting temperature nickel is chemically negative to iron, which is capable of reducing its oxides and preventing its oxidation, even when the bath is a highly oxidizing one. Nickel may, therefore, be added to the bath at any time practically without

any loss or waste, but its addition is usually made just long enough before tapping to enable it to become properly diffused. For the same reason nickel cannot deoxidize iron, neither will it decompose carbon monoxide nor hold other gases in solution, though it is said to prevent, or hinder in a measure, the segregation of carbon and the other metalloids. It is not used, then, for a curative agent, but only for its beneficial effect upon the physical properties of the steel, for which purpose it is preeminently a strength giving element.

The Different Nickel Steels and Their General Characteristics: The nickel content of the useful nickel steels varies from .5 per cent. to 46 per cent., which is a wider range than that covered by any other alloying element. Below 2 per cent. the benefits derived from its addition alone to structural steel that is to be used without treatment, are very slight and are not worth the extra cost. In the case of some steels, however, that are subjected to some special treatment, such as case hardening, after forming, a nickel content as low as .50 per cent. may be used to impart additional toughness to the metal. The great bulk of simple nickel steel, containing from .50 to 4 per cent. nickel, is used for such structural purposes as bridges, heavy forgings, steel rolls, and various parts of machines, especially engines, large dynamos and automobiles, because of the superior mechanical properties imparted by the metal when added to steel in these amounts. Thus, for each 1 per cent. of nickel added above 2 per cent. and up to 4.00 per cent. an increase of approximately 6000 pounds in the tensile strength of this steel over the carbon steel is noted, while only a slight decrease, if any, in the ductility occurs, and this improvement is secured without any heat treatment whatever. The best results, costs and benefits considered, appear to be obtained when the nickel content is between 3 and 4 per cent., the content aimed at for ordinary structural purposes being 3.25 per cent. to 3.50 per cent. This steel also resists rusting and abrasion better than the plain carbon steels. Nickel steel of this grade lends itself well to heat treatment, and may also be used for case hardening, the only objection to its use for this purpose being the slight tendency of the nickel to retard the rate of penetration of the carbon. When the nickel content is raised above 5 per cent., the metal becomes very hard, is difficult to work either hot or cold, and is rolled only by taking the greatest care. It is in demand where great resistance to shock is a prime quality. Up to 8 per cent., nickel increases the hardness of the steel to which it is added, but leaves the metal still amenable to heat treating. Steels containing 10 per cent. or more of nickel cannot be hardened by quenching, but become softer after being subjected to this heat treating operation. In 1914 a new alloy steel, containing 13 per cent. nickel and .55 per cent. carbon, was discovered by Arnold and Read. It is so hard that it cannot be machined or drilled, has a yield point of 134000 pounds, a tensile strength of 195000 pounds, and an elongation of 12 per cent. in two inches. Before this discovery, 15 per cent. nickel steel, tensile

strength about 170000 pounds, was thought to be the strongest one of the series. This steel has been employed occasionally for shafting. Nickel steel containing 22 per cent. nickel is used when resistance to rusting is the prime consideration. Thus, it was employed in the valve stems of the salt water fire protective system installed by the city of New York, and in similarly exposed parts of the pumps used in the drainage system for the city of New Orleans. It is also said to be suitable for the spark poles in spark plugs for internal combustion engines. 24 per cent. to 32 per cent. nickel steel is used for electrical resistance, such as those employed in irons, toasters, and other household heaters. Nickel steels with a nickel content of about 24 per cent. are non-magnetic. 36-per cent. nickel steel is characterized by an extremely low coefficient of expansion, hence is used in balance wheels of watches, the pendulums of clocks, etc., in order to dispense with compensation. It is known as invar. Finally, 46-per cent. nickel steel, containing only .15 per cent. carbon, is known as platinite, because it has about the same coefficient of expansion as platinum and glass. Hence, it is employed in the lead wires of incandescent lamp bulbs, where formerly platinum was held to be indispensable. Later, a 38-per cent. nickel steel wire, coated with copper, was found to give better satisfaction than platinite.

Reasons for These Peculiarities of the Nickel Steels: A study of the explanation offered to account for the peculiar influence of nickel upon steel is both interesting and instructive. Referring again to the 3.5-per cent. nickel steel, it is to be noted that nickel primarily influences the strength of the steel, and, to a less degree, the ductility. These facts are explained when the solubility of nickel in iron is considered. Thus, when nickel is added to steel, say of hypo-eutectoid composition, it dissolves in the iron to form an iron-nickel alloy. When this steel is cooled through the critical range, it is this alloy that replaces both the free ferrite and the pearlitic ferrite of the carbon steel. Naturally, a change in the physical properties due to this fact alone are to be expected. But it is in the influence of this alloy upon the formation of pearlite that the reason for the great increase in tensile strength of nickel steel is found. The separation of the cementite from the iron-nickel-carbon solution does not take place as readily as from a plain iron-carbon solution, hence the pearlite areas are larger and less clearly defined than in plain carbon steels. In other words, just as carbon and rapid cooling are obstructing agents to the transformation from austenite to pearlite, so also does the nickel act in a similar manner. As long as the nickel content is very low, not over 2 per cent., this influence shows itself only in a slight change in the physical properties as noted. These changes become more marked with increase of nickel, as is to be expected, but the quick change in heat treating properties at 8 per cent. or 10 per cent. and at about 25 per cent. are not thus accounted for. A little reflection, however, shows all these characteristics to be due to the same cause, namely, the retarding action of the nickel upon the trans-

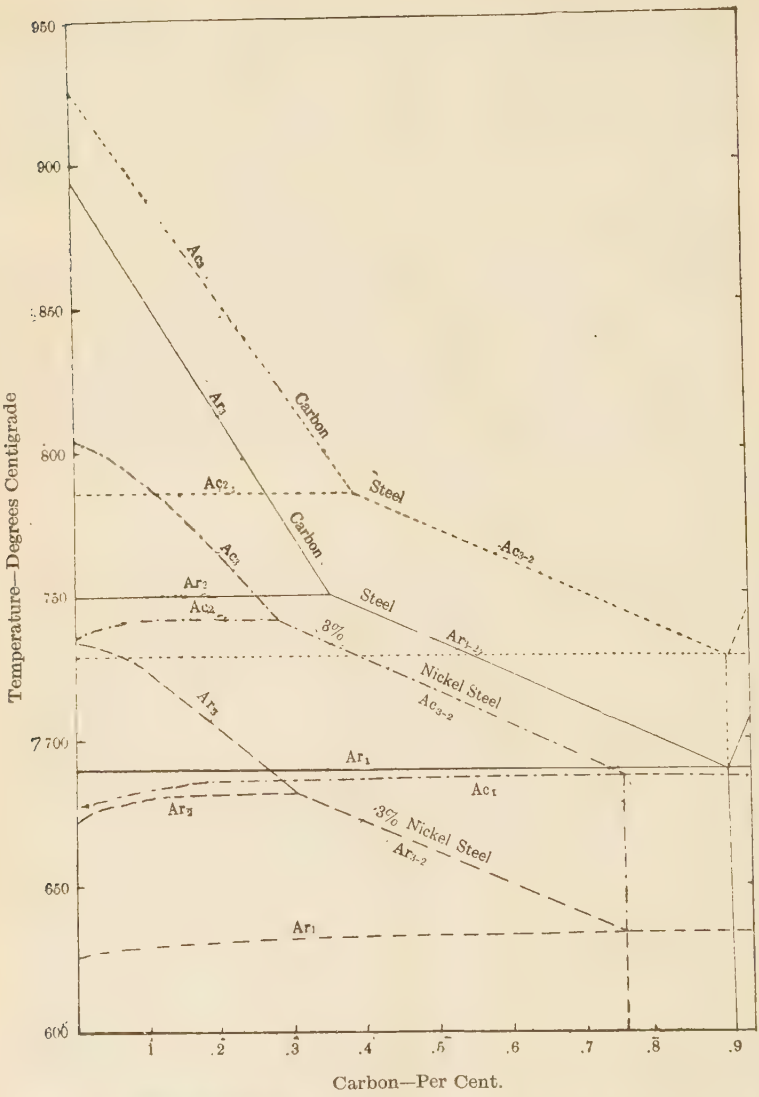


Fig. 207. Diagram Showing effect of Nickel Upon the Critical Ranges. Compared with Carbon Steel. Slow cooling from just above Ac_{3-2}. (After Bullens, Steel and its Heat Treatment.)

formation ranges. One writer represents this influence of nickel upon the critical points in heating as follows:

.01% Nickel lowers the Ac_3 range .235° C.
.01% " " " $Ac_{3\text{-}2}$ range .180° C.
.01% " " " Ac_2 range .087° C.
.01% " " " Ac_1 range .103° C.

No figures can be given for the Ar. points, because the exact location of these points changes not only with the nickel content, but also with the rate of cooling and the distance above the Ac. point to which the steel is heated before cooling begins. With slow cooling from just above Ac. and a nickel content of about 3 per cent., the Ar. points are about 80° C. below the Ac. points. In addition to and in connection with these facts, the effect of nickel upon the eutectoid ratio should also be considered. The statement that nickel interferes with the free formation of pearlite has already been made, and it now remains to be pointed out that nickel, up to about 8 per cent., reduces the eutectoid ratio below that for straight carbon steels. According to Bullens the eutectoid for a steel containing 3 per cent. nickel is reached when the carbon content is .75 per cent. and for one containing 7 per cent. nickel this value falls to .60 per cent. carbon. All these facts, as they relate to the 3 per cent. nickel steel, which is the one we are most interested in, have been assembled and are represented in the diagram on the opposite page, which was copied after Bullens, who was the first to represent the effects of nickel in this way. This diagram is intended to depict the general effects of nickel upon the transformation ranges, which become lower and lower as the nickel content is increased, and the eutectoid ratio which decreases with increase of nickel. The diagram shows the position of the Ac and Ar points for carbon steel and also for steel containing 3 per cent. nickel. Thus:

Solid line indicates the position of the ranges on cooling carbon steel.

Dotted line indicates the position of the ranges on heating carbon steel.

Dot and dash line indicates the position of the ranges on heating 3-per cent. nickel steel.

Dash and dash line indicates approximately the position of the ranges on cooling 3 per cent. nickel steel. For reasons already mentioned, the Ar. points are subject to considerable variation.

When the nickel content has been increased to 25 per cent., these ranges are found to lie in a position that is entirely below atmospheric temperatures.

Structural Changes Due to Nickel: From the preceding data a simple calculation will show that as the nickel, or nickel and carbon contents, are increased, the transformation ranges are progressively lowered until they reach atmospheric temperatures. This fact forms a basis for the classification of the nickel steels, which are divided into the following three divisions:

1. **Pearlitic-Nickel Steels** are those in which the nickel and carbon contents are such that, when slowly cooled from a high temperature, they will consist in whole or in part of pearlite. In these steels the nickel ranges from 0 to 10 per cent. and follows inversely the percentage of carbon, which theoretically ranges from 0. to 1.60 per cent.

2. **Martensitic-Nickel Steels:** In these steels the nickel and carbon contents are high enough to lower the critical ranges to such a degree that only a partial transformation from austenite to pearlite occurs even on slow cooling. In these steels the nickel contents range from 10 per cent. to 25 per cent. with the carbon varying as above.

3. **Austenitic-Nickel Steels:** Above 25 per cent. the influence of the nickel is so great that the transformation range is lowered to atmospheric temperatures, and the steel is always austenitic regardless of the carbon content. As previously pointed out, the pearlitic steels containing less than 4 per cent. nickel are of most importance commercially.

The Constitutional Theory of Ternary Steels: In causing these structural changes the action of nickel is in accord with that of all the

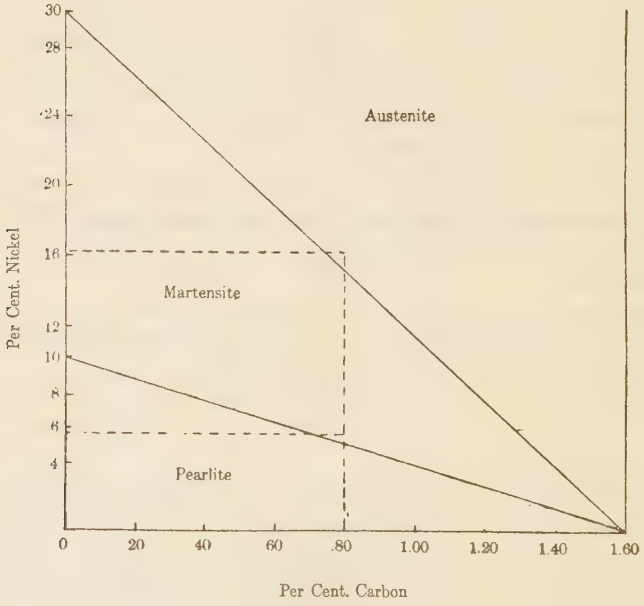


Fig. 208. Constitutional Diagram for the Nickel Steels. (After Guillet).

alloying elements. Briefly stated, the theory is that, upon the introduction of a third element into a given carbon steel, the steel remains at first pearlitic in structure, but as the content of the special element is increased the steel becomes martensitic, then austenitic or cementitic, depending upon the chemical action and alloying powers of the special element with respect to carbon and iron; and also that by keeping the amount of the special element constant, the same transformations may be effected by raising the carbon content. This statement, in so far as it relates to nickel steels, is expressed diagrammatically in the figure on the opposite page.

This diagram shows that with a very low carbon content, say about .05 per cent., the steel remains in the pearlitic condition until the nickel content reaches 10 per cent., when it will be found to be in the martensitic condition after slow cooling. With a nickel content of 30 per cent. the same steel would be austenitic. But with a carbon content of about .80 per cent., for example, the steel becomes martensitic when the nickel content exceeds 6 per cent., and austenitic when it reaches 16 per cent. or 17 per cent. Diagrams like the preceding are useful in illustrating the effect of the different alloying elements and will frequently be made use of in the discussions to follow.

Heat Treating Pearlitic Nickel Steels: From what has been said, it should be apparent that the heat treating of nickel steel, to secure the desired results, is an art that requires much experience and knowledge. Hence, it is only desirable to indicate what should be the proper treatment for this steel, and although the heating and cooling of this steel presents some phenomena quite distinctive from carbon steels, it is considered that this object has already been attained. However, a few remarks as to how the low nickel steels are benefited by heat treatment may not be out of place. A heat treated nickel steel has a lower reduction and elongation than a correspondingly heat treated steel without nickel, but the increase in strength is much greater. Thus, for the same strength, the nickel steel is much tougher, and on this account nickel is much to be preferred to carbon for increasing tensile strength. The tensile strength and elastic limit are both affected by the temperature of the drawback, being decreased as this temperature is raised, but the reduction in area and elongation are not so correspondingly and gradually increased as in the plain steels. In this connection, a study of tables 70 and 73 will be found of value.

Table 73: Illustrating the Effect of Various Heat Treatments upon the Mechanical Properties of Three Per Cent. Nickel Steels.

Chemical Composition: C. .37%, Mn. .61%, Si. .22%, P. .022%, S. .034%, Ni. 3.27%.

Description of Pieces Treated: One inch rounds, 25 inches long; 14 pieces, all from same billet.

Description of Test Pieces: One test piece from each of the 14 pieces, turned to a diameter of ½ inch, as in Fig. 111.

HEAT TREATMENT		PHYSICAL TEST					
Hardening and Refining, Deg. C	Anneal and Draw, Deg. C	Tensile Strength	Elastic Limit	Elongation in 2″ %	Reduction in area %	Brinell Number	Scleroscope Test
As Rolled	....	113,000	69,000	22.5	47.7	229	32
Heated to 760° and cooled in Furnace		99,000	60,000	26.1	48.3	183	26
Heated to 815° quenched in oil	427°	168,000	150,000	13.5	47.2	331	48
	482°	148,000	131,000	18.0	48.3	285	44
	538°	133,000	118,000	21.0	57.3	262	40
.....	593°	110,000	90,000	28.0	64.7	217	33
.....	649°	104,000	70,000	28.0	63.0	207	27
.....	704°	95,000	62,500	28.5	51.7	179	26
Heated to 815° quenched in water	427°	185,000	165,000	13.0	51.1	352	50
	482°	150,000	136,000	17.5	47.2	311	44
	538°	148,000	135,000	16.0	54.7	293	44
.....	593°	133,500	115,000	18.5	56.5	269	37
.....	649°	108,000	80,000	27.5	62.8	223	32
.....	704°	98,000	67,000	28.0	58.6	179	29

SECTION III.

CHROME STEEL.

The Manufacture of Simple Chromium Steels is carried on by the open hearth, the electric, or the crucible process. At the temperature of molten steel, chromium is capable of reducing iron oxides, hence it is oxidized to a great extent in the open hearth, especially during the melting and boiling of the charge. All simple chrome steel is made by the addition of ferro-chromium to the charge. When the steel is made in crucibles, the ferro-chromium is added with the original charge; if in the electric furnace, this addition may be made at any time; but if made in the open hearth furnace, the ferro-chromium is added to the steel just long enough before casting for the alloy to be melted and become well mixed through the charge, as otherwise great waste of the chromium results. Chromium, however, is not oxidized readily enough to be of any value as a curative or a deoxidizing agent, and is used only for its effect as an alloying element. Simple chromium steels are worked by the same methods and in the same way as carbon steels, but unlike nickel steels, they are seldom, if ever, used in their natural state, heat treatment being necessary to develop the beneficial effects of the chromium, which is most active in responding to this treatment. Simple chromium steel was one of the first alloy steels to be made.

Influence of Chromium: This element is preeminently a hardening agent in steel. Unlike nickel, which merely dissolves in iron, chromium forms a carbide. In steel, therefore, at least a part of the chromium will be in this form; but it never reacts with the carbon to the exclusion of iron, and in steel this carbide may exist either as iron-chromium carbide, $xFe_3C{\cdot}yCr_3C_2$ or as a solution of Fe_3C and Cr_3C_2. Thus, while nickel is found in the ferrite of the steel, chromium is associated with the cementite, and imparts what might be termed a mineral hardness to the steel. But the great hardness of the chrome steels is due, also, to another cause. This iron-chromium cementite is not as readily dissolved or diffused as the ordinary cementite on heating the steel through the critical range, nor does it segregate, or separate to form pearlite, as readily on cooling. This fact accounts for the peculiar changes in the critical ranges of the steel that the addition of small amounts of this element brings about, for while it tends to raise the Ac range it also lowers the Ar range. Thus, in quenching it helps to prevent the transformation of the austenite, and so adds much to the hardness in this way. From these statements it is to be inferred that chromium may have no hardening power when not in the presence of carbon. Such a conclusion agrees with the facts, as it has been shown by Harbord that very low carbon chrome steels have practically no hardening power. It is now, also, easily understood why the degree of hardness of the steel is dependent, within certain limits, upon

the carbon content as well as upon the chromium. An exceedingly fine grain structure is characteristic of heat treated chrome steels, which fineness of grain confers the valuable property of toughness. Thus, the net result from the influence of this element is to increase the tensile strength and elastic limit, without a noticeable loss in the ductility. One investigator has found chromium to be very efficient in retarding corrosion of the steel by neutral media, such as sea water, and, therefore, recommends its use in ship plates. A higher content of chromium, 12 to 14 per cent., makes steel very resistant to corrosion. (See p. 786.)

The Microscopic Constituents of the Chrome Steels: The influence of chromium and carbon in determining the constitution of the steel is shown in the accompanying diagram.

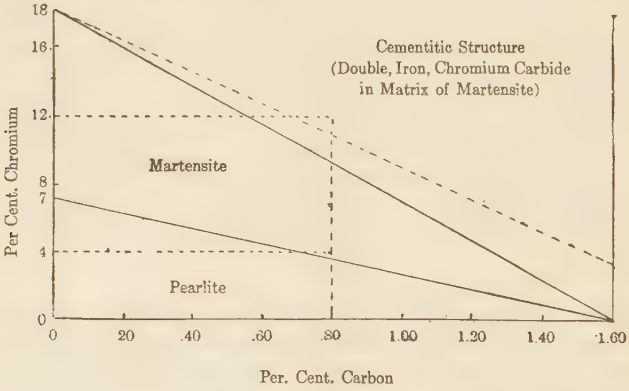


Fig. 209. Constitutional Diagram for Chromium Steels. (After Guillet).

From this diagram it is seen that, when the chromium content exceeds 7 per cent. in steels of low carbon content, or about 5 per cent. in steels of high carbon content, the steel is composed of martensite even if cooled slowly from above the critical range, hence is very hard and strong, but is lacking in ductility and is inclined to be brittle. These steels can be softened somewhat, however, by heating for a long time at a temperature of about 750° C., because such treatment spheroidizes the carbides and robs them of their hardening effect. It will be noted that, unlike nickel, increasing the chromium content beyond a certain limit in a steel with a given carbon content fails to produce the austenitic condition, but gives a new structure made up of grains of the double carbide embedded in martensite. Between these two areas is a narrow range in which the carbide grains are somewhat less numerous than in the cementite region proper. This range marks the gradual transition from the martensitic to the cementitic condition with the gradual increase in the chromium and the carbon content. Like the martensitic condition, steel of cementitic

composition hardens in air. For obvious reasons, then, to produce structural steels of greatest usefulness, the chromium content will be restricted to that required to give the pearlitic condition only.

Uses of the Simple Chrome Steels: The pearlitic chromium steels are used wherever extreme hardness is desired. Thus, they have long been used for stamp shoes and dies for crushing hard ores, like some of the gold and silver ores. Another use is for five-ply plates for safes, where their great hardness is valued on account of the resistance they offer to the drilling tools used by burglars. Rolls for cold rolling metals are made of steel containing about .9 per cent. carbon and 2 per cent. chromium, while several thousand tons of steel containing about 1.30 per cent. carbon and .5 per cent. chromium are used annually for files. It is often used in steel for various special purposes, as for example the steel known by the name of "Crucia," which is nothing more than a good grade of spring steel to which has been added from .20 per cent. to .40 per cent. chromium. The Carnegie Steel Company manufactures this steel as a part of their regular product. A type for axes and hammers, which contains .60 per cent. to .70 per cent. carbon and .60 per cent. to .90 per cent. chromium; another for chains, containing .25 per cent. to .33 per cent. carbon and .65 per cent. to .95 per cent. chromium; and a third for track bolts with .25 per cent. to .40 per cent. carbon and .60 per cent. to .90 per cent. chromium are also manufactured by this company. But the most important use for these steels is in the balls and rolls for bearings. For this purpose they are employed in low carbons for case hardening and in high carbons for heat treating, i. e., quenching and tempering. Of the tonnage furnished by Carnegie Steel Company for this purpose, that for case hardening is made in the open hearth, while the high carbon material is produced in the electric furnace.

Heat Treatment of Simple Chrome Steel: To cite an example of the high grade of chrome steel: One large maker of bearings uses steel containing carbon, 1.10 per cent.; chromium, 1.40 per cent.; manganese, 0.35 per cent.; sulphur, 0.025 per cent.; and phosphorus, 0.025 per cent. Sizes smaller than one-half inch diameter are heat-treated by being quenched in water from 774° C. (1425° F.) and then drawn to 190° C. (374° F.) for half an hour. For larger balls, the quenching temperature is 802° C. (1476° F.). The second heating does not produce even an oxide color, but is enough to relieve in some degree the internal stresses due to the irregular cooling of quenching, so that the balls are less liable to crack spontaneously or to be broken in use. The strength of a good, well-treated ball is prodigious; a ball three-fourths of an inch in diameter, tested by the three-ball method, sustained a load of 52,000 pounds. On the small area of contact the intensity of the pressure amounts to over one million pounds per square inch. The Society of Automotive Engineers recommends less chromium than that given above, or 1 to 1.2 per cent. The critical

ranges for these steels containing .90 per cent. carbon, vary about as follows:

For a chromium content of .50 per cent., from 720° C. to 745° C. (1328° to 1373° F.).

For a chromium content of 1.50 per cent., from 760° C. to 785° C. (1400° to 1445° F.).

As indicating what may be expected by varying the treatment of the steels of this grade, the following will serve as an illustration:

Table 74. Physical Properties of a Heat Treated Chrome Steel.

Material: 1 inch rounds.
Analysis: C., .64%; Mn., .27%; Si., .18%; Cr., 1.01%.
Treatment: Heated to 870-871° C. Quenched in oil, and tempered as indicated.

Tempering Temperatures	Tensile Strength	Elastic Limit	Elongation in 2 Inches	Reduction in Area	Brinell Hardness
400° C.	228,000	170,500	5.2%	13.7%	478
500° C.	212,500	155,500	8.4%	19.8%	445
600° C.	186,500	128,000	10.3%	22.2%	389

SECTION IV.

CHROME—NICKEL STEELS.

Influence of Chromium and Nickel When Combined: Having considered the effects of chromium and nickel when added separately to the steel, the student is interested in knowing what their combined influence may be. In the words of Bullens, an impartial judge of high standing as an authority upon the subject of alloy steels, especially from a practical standpoint: "The chrome-nickel steels probably represent the best all-round alloy steels in commercial use for general purposes. Chrome-nickel steels of suitable composition appear to have combined in them the beneficial effects of both the chrome and nickel, but without the disadvantages which are inherent in the use of either one separately. Moreover, the presence of both chrome and nickel seems to intensify certain physical characteristics. To the increased ductility and toughness conferred by nickel on the ferrite there is added the mineral hardness given to the cementite and pearlite by the chrome, but with a greater resultant effect. Again, while the addition of nickel alone serves to diminish the susceptibility to brittleness in the steel upon prolonged heating or sudden cooling—in comparison with the corresponding straight carbon steels—and, on the other hand, the presence of chrome alone tends to the opposite effect, a suitable combination of the two alloying elements tends to neutralize the harmful effects and also to magnify the good points. This is not only brought out in the static strength and ductility, but also in the dynamic strength or fatigue resistance."

Types of Chrome-Nickel Steel: According to the testimony of some heat treating experts there appears to be a certain ratio of chrome to nickel which gives the most efficient combination of the physical properties. Thus, if the nickel and chromium are present in the right proportions, the lesser susceptibility of the nickel to brittleness, for example, will so modify the greater tendency to brittleness which is given by chrome alone, that a better steel is obtained than when this ratio is not observed. This ratio is said to be about 2½ parts of nickel to one part of chromium. Furthermore, it is claimed that if the chromium content greatly exceeds this relation to nickel, the temperature limits are so narrowed that the successful treatment of the steel is made very difficult. Thus, in the three standard types of these steels, known as low nickel-chrome steel containing about 1.5 per cent. nickel, medium nickel-chrome steel with about 2.50 per cent. nickel, and high nickel-chrome steel, in which the nickel content rises to that of the simple nickel steels with 3.5 per cent. nickel, the chromium content should be approximately .60 per cent., 1.00 per cent. and 1.50 per cent., respectively.

Mayari Steel, termed a natural chrome-nickel steel, is made from certain ores found at Mayari, Cuba. These ores contain enough nickel and chromium to give a pig iron with 1.3 per cent. to 1.5 per cent. nickel and 2.5 per cent. to 3.0 per cent. chromium. When this iron is converted into steel, for which purpose the open hearth or the duplex, Bessemer-open hearth, processes are employed, practically all the nickel remains in the steel, but a large part of the chromium is wasted. The steel is thus a species of low-nickel-chrome, containing roughly from 1.00 per cent. to 1.50 per cent. nickel and from .20 per cent. to .70 per cent. chromium. This steel is undoubtedly of excellent quality for certain purposes, but where the highest quality of chrome-nickel steel is required, most authorities agree that the synthetic alloy steels are superior.

Uses of Chrome-Nickel Steels: Low chrome nickel steel is the type more commonly employed because of its low price and the greater ease by which it is machined. In static properties it is nearly equal to the higher nickel grades, but in resistance to dynamic stresses, shocks, etc., the latter are superior. Besides, since the purpose to which it is adapted is about the same as 3.5-per cent. simple nickel steel, low-nickel chrome is being substituted for this steel, also on account of the price. All three grades are used in automobiles, the carbon content being varied about as shown in the following table:

Table 75: Grades and Composition of Nickel-Chrome Steels.

Grade	Carbon %	Mn. Max. %	Si. %	S. Max. %	P. Max. %	Ni. %	Cr. %
Low.....	0.20 to 0.55	0.70	Low	0.050	0.04	1.25	0.60
Medium..	.20 to .55	.70	Low	.050	.04	1.75	1.10
High.....	.20 to .55	.70	Low	.050	.04	3.50	1.50

An important use of these steels is in armor plate. Thick armor is face hardened by a carbonizing process, but the body has the original composition, which is approximately as follows: C., .33 per cent.; Mn., .32 per cent.; S., .03 per cent.; P., .014 per cent.; Si., .06 per cent.; Ni., 4.00 per cent.; and Cr., 2.00 per cent. Medium armor, three to five inches in thickness, is not face hardened, but is given high properties throughout by the proper heat treatment. The composition of this armor is approximately, C., .30 per cent.; Mn., .34 per cent.; S., .03 per cent.; P., .03 per cent.; Si., .13 per cent.; Ni., 3.66 per cent., and Cr., 1.45 per cent. The nickel chromium steels are used in the manufacture of most armor piercing projectiles, also.

Heat Treatment of Chrome-Nickel Steels: The heat treatment of these steels is about the same in kind and method as that for simple nickel and chrome steels, and is varied to suit the kind of material and the purpose for which the steel is to be used. To give a general idea of the proper treatment for these steels, the recommendations of Bullens may be cited:

I. "For forgings:
   a. Quench in oil from about 175° to 200° F. (97° to 110° C.) over the critical range.
   b. Quench in oil from about 50° F. (28° C.) over the critical range.
   c. Anneal at about 75° F. (42° C.) under the critical range and machine.
   d. Quench in the proper medium from about 50° F. (28° C.) over the range.
   e. Draw the temper to suit the work in hand."

II. "For shafts and other structural parts in which the desired physical properties may be obtained by a drawing temperature of about 900° F. (500° C.) or over, and which will leave the steel in a machinable condition, treatment I. may be modified at (c) as thus noted, and no further treatment will be required.
   a. Quench in oil from about 175° to 200° F. (97° to 110° C.) over the critical range.
   b. Quench in oil from about 50° F. (28° C.) over the critical range.
   c. Draw at 900° F. (482° C.) or more, as the work may require. Machine."

III. "The full treatment as given under I. may be modified, if desired, to the following, for parts to be drawn below 900° or 1000° F. (482° or 540° C.).
   a. Quench in oil from about 175° to 200° F. (97° to 110° C.) over the critical range.
   b. Reheat to about 25° to 50° F. (14° to 28° C.) over the critical range and cool slowly. Machine.
   c. Quench in oil from about 50° F. (28° C.) over the critical range.
   d. Draw to the temperature required by the work."

The data supplied in tables 76 and 77 will serve as a basis for comparing the mechanical properties of the chrome-nickel steels, both in their natural and heat-treated states.

Table 76: Illustrating the Effect of Various Heat Treatments upon the Mechanical Properties of Low-Chrome-Nickel Steels.

Chemical Composition: C. .39%, Mn. .52%, Si. .18%, P. .017%, S. .042%, Ni. 1.18%, Cr. .58%.

Description of Pieces Treated; One inch rounds, 25 inches long; 14 pieces, all from same billet.

Description of Test Pieces; One test piece from each of the 14 pieces, turned to a diameter of ½ inch, as in Fig. 111.

HEAT TREATMENT		PHYSICAL TESTS					
Hardening and Refining Deg. C	Anneal and Draw, Deg. C	Tensile Strength	Elastic Limit	Elongation in 2" %	Reduction in area %	Brinell Number	Scleroscope Test
As Rolled	....	99,000	59,000	25.5	54.4	208	29
Heated to cooled in Furnace	760° and	89,000	54,000	30.0	56.5	170	25
Heated to 845° quenched in oil	427°	139,000	114,000	15.5	51.4	331	42
	482°	130,000	113,000	15.0	53.9	321	44
	538°	113,000	88,000	17.5	59.8	255	34
	593°	113,000	86,000	21.0	62.8	229	32
	649°	108,000	81,000	25.0	64.7	229	31
	704°	97,000	70,000	27.0	67.7	207	29
Heated to 845° quenched in water	427°	174,000	158,000	14.0	47.2	363	46
	482°	150,000	135,000	16.5	45.7	221	44
	538°	140,000	125,000	20.0	55.2	285	44
	593°	124,000	108,000	22.0	60.8	255	40
	649°	110,000	91,000	26.0	66.0	229	33
	704°	90,000	70,000	34.0	69.2	187	25

Table 77: Illustrating the Effect of Various Heat Treatments upon the Mechanical Properties of High-Chrome-Nickel Steel.

Chemical Composition; C. .34%, Mn. .64%, Si. .20%, P. .010%, S. .036%, Ni. 3.65%, Cr. 1.24%.

Description of Pieces Treated; One inch rounds, 25 inches long; 14 pieces, all from same billet.

Description of Test Pieces; One test piece from each of the 14 pieces, turned to a diameter of ½ inch, as in Fig. 111.

HEAT TREATMENT		PHYSICAL TESTS					
Hardening and Refining Deg. C	Anneal and Draw, Deg. C.	Tensile Strength	Elastic Limit	Elongation in 2" %	Reduction in area %	Brinell Number	Scleroscope Test
As Rolled	....	172,500	138,000	11.5	26.5	444	57
Heated to 760° and cooled in Furnace		125,000	78,000	18.0	47.2	255	38
Heated to 845° quenched in oil	427°	190,000	166,000	12.5	50.0	415	55
	482°	170,000	154,000	15.0	44.3	341	41
	538°	142,000	126,000	20.0	57.8	321	43
	593°	127,500	115,000	22.0	62.3	285	36
	649°	117,000	99,000	23.0	64.7	255	37
	704°	115,000	69,000	24.0	56.0	255	35
Heated to 845° quenched in water	427°	164,000	152,000	17.5	56.0	375	51
	482°	160,000	147,500	15.5	53.9	341	48
	538°	145,000	130,000	21.0	58.6	321	43
	593°	124,000	100,000	22.5	62.8	269	40
	649°	120,000	99,000	24.0	63.7	248	36
	704°	120,000	69,000	17.0	50.0	269	36

SECTION V.

VANADIUM STEELS.

Simple Vanadium Steels for structural purposes do not at present have the standing they formerly had, and the only reason for mentioning them here is to enable the reader to get an idea of the effects of vanadium alone, so that he can better understand the reasons for chrome vanadium steel, to be considered later. Since 1917 the Carnegie Steel Company has manufactured but one grade of vanadium steel, known as type "F," which is used as a flux in oxyacetylene, oxyhydrogen, and electric welding.

Influence of Vanadium: Unlike nickel and chromium, vanadium is an intense deoxidizing agent, being capable of carrying the cleansing of the steel beyond the point obtainable by manganese, or even silicon and aluminum. Thus, this element performs the double function of a curative and an alloying element. It is added to the steel, in the form of ferro-vanadium, containing about 35 per cent. of the element, at the time of tapping, if the steel is being made by the open hearth process, and preferably after the other ladle additions to avoid undue wastage. Of the vanadium that is retained by the steel, only very small amounts, from .15 per cent. to .25 per cent., are required to affect the physical properties of the steel. Like most of the alloying elements, it tends to give a finer and denser structure than that of carbon steel, and for the most part its action is similar to other alloying elements. But in some respects, at least, it presents characteristic phenomena. Thus, there are good reasons to believe that, when present even in the small amounts noted above, it is both dissolved in the ferrite, like nickel, and exists as a carbide or a double carbide in the cementite, like chromium. It has a powerful influence upon the transformation ranges, as is seen from the fact that while steels containing .2 per cent. carbon and .7 per cent. vanadium, or .8 per cent. carbon and .5 per cent. vanadium, are pearlitic, any increase of the vanadium content over these limits renders the steel cementitic as shown in the following diagram:

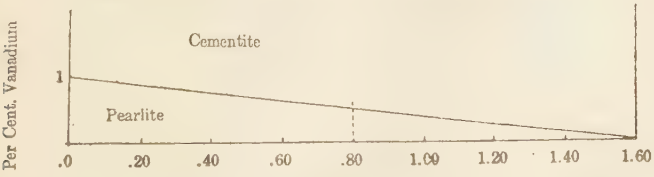


FIG. 210. Constitutional Diagram for Vanadium Steels. (After Guillet).

As revealed by the static physical tests, the benefits from vanadium are somewhat similar to those for the pearlitic nickel steels, that is, it gives a combination of high elastic limit and ductility. With proper heat treatment, it is also said to resist shock, alternate stresses, wear and fatigue.

SECTION VI.

CHROME-VANADIUM STEELS.

Effect of Combining Chromium and Vanadium: In order that the influence of vanadium as indicated above may be realized to the fullest, the presence of another element as an intensifier is required. Just as chromium intensifies the influence of nickel, so does it also stimulate vanadium, but to a much greater degree, it is said, than with the former. Hence, though various combinations have been tried, such as vanadium-nickel, chrome-vanadium-nickel, etc., the tendency at present points to the general adoption of the one combination, chrome-vanadium.

Properties and Uses of Chrome-Vanadium Steels: The hot working of these steels presents no difficulties, the steel behaving under the hammer or in the press or rolls much like the higher carbon plain steels. In physical properties, they are similar to chrome-nickel steel except that their contraction of area for a given elastic limit is a little greater. They are also said to be more easily machined than chrome-nickel steel and are more free from surface defects, such as scale-pits and seams. While some enthusiasts maintain that it is the steel best adapted to resist shock and fatigue, others hold that the chrome-nickel steel answers all requirements just as well. Perhaps the truth of the matter is that, while both steels are available for most purposes, there are limited fields in which one may excel the other and in which each has its own sphere of usefulness. Most of the chrome-vanadium steel made by the Carnegie Steel Company is used for driving axles and other forgings for locomotives, automobile springs and axles, compressed air flasks, torpedo tubes, etc. They are nearly always heat treated before being put into service, but in some automobiles the frames, and even part of the forgings and shafts, are made of the steel in its natural state. The composition and properties of three grades of this steel in the untreated condition are given herewith.

Table 78. The Composition and Mechanical Properties of Untreated Chrome-Vanadium Steels.

	COMPOSITION							TENSILE PROPERTIES			
Grade No.	C. %	Mn. %	Si. %	S. %	P. %	V. %	Cr. %	Tensile Strength, Pounds	Elastic Limit, Pounds	Contraction of Area, %	Elongation in 2 Inches%
1	0.57	0.84	0.27	0.04	0.01	0.31	1.36	142,000	114,000	42	14
2	.46	.48	.20	.03	.01	.14	1.17	125,000	95,000	55	20
3	.18	.32	.18	.03	.01	.20	.74	65,000	47,200	62	23

Some idea of the general results obtained from heat treating the chrome vanadium steels and of the methods employed may be gained from the following table:

Table 79. Physical Properties of Treated Chrome-Vanadium Steels. Tests made on Small Rolled Sections.

CHEMICAL COMPOSITION				HEAT TREATMENT		MINIMUM PHYSICAL RESULTS AFTER TREATMENT			
Carbon Per Cent	Manganese, Per Cent.	Chromium, Per Cent.	Vanadium, Per Cent.	Water Quenched, Deg. C.	Draw Deg. C.	Tensile Strength, Lbs. per Sq. In.	Elastic Limit, Lbs. per Sq. In	Elongation in 2 In. Per Cent.	Reduction of Area, Per Cent.
* .19	.49	.96	.23	850	749	101,400	91,200	27	69
...	...	...	...	....	712	109,500	98,800	24	66
...	...	...	...	....	675	121,200	113,100	22	66
...	...	...	...	....	635	129,600	121,200	21	60
...	...	...	...	....	596	136,000	125,700	20	60
...	...	...	...	....	574	146,900	137,200	20	58
* .25	.30	.85	.14	850	748	88,640	78,960	29	77
..	...	...	...	....	697	98,520	92,200	26	72
. .	...	...	...	....	657	118,700	114,100	24	72
...	...	...	.	....	607	121,800	118,200	22	69
...	...	...		....	574	132,400	125,800	20	64
†.38	.41	.97	.24	815	704	100,000	88,000	27	65
...	...	...	...	....	649	118,000	101,000	23	60
...	...	...	...	....	593	130,000	108,000	18	52
...	..	...	...	....	538	130,000	108,000	16	50
...	.	. .	...	....	482	157,500	142,000	15	47
...	..	...	..	....	427	177,500	155,000	11	36
				Oil Quenched					
...			.	815	700	95,000	75,000	30	65
...		. .	. .	....	650	117,000	98,000	20	57
...			.	....	595	125,000	105,000	18	56
...		..		....	540	133,000	113,000	18	50
...	...	...	...	....	480	143,000	116,000	16	48
...	..	...	...	....	430	149,000	120,000	15	49
...	.	..	..	Annealed	760	88,500	58,000	30	59
...	...	...	...	As Rolled	...	127,500	96,500	20	48

*Silicon .05%. Phosphorus under .035%. Sulphur under .04%.
†Silicon .25%. Phosphorus .021%. Sulphur .041%. Tests on 1″ rounds.

SECTION VII.

MOLYBDENUM STEELS.

History and Uses of Molybdenum Steels: Like manganese, silicon and vanadium, molybdenum may play a double part in the manufacture of steel, but unlike these elements it cannot act as a cleansing agent. It is used, therefore, only in the production of alloy steels, and in this division it functions in two widely different fields. In amounts ranging from one to eight per cent. it is used in conjunction with other elements to produce high speed tool steels, and in smaller quantities than one per cent. it is employed in various grades and types of structural steels. While its use in the latter class of steels is of recent origin, the investigation of the steel-alloying properties of this element was begun prior to 1894, and a very thorough study of the use of this element in steel was made by Leon Guillet in 1902-3. From 1900 to 1915 its use was restricted to high speed steels, in which it was substituted in whole or in part for tungsten. During this period its inferiority to tungsten for high speed tool steel was generally conceded in this country, while the study of its use in steels for structural purposes was continued by at least five different investigators, all of whom testified to certain beneficial effects of the element when used for this purpose. In spite of these favorable reports, however, the use of this element in structural steels was held back, because, owing to the high cost of extracting the element from its ores, the poor quality of the alloys suitable for the purpose and the uncertainty of the supply, it could not be made to compete with other alloying elements, such as nickel, chromium and vanadium. With the advent of the World War, the prices of these more widely used elements rose rapidly, their supply became less certain, the demand for high quality steels increased, and the largest known supply of molybdenum ore in the world was discovered within our own boundaries, which made an uninterrupted supply of the element certain. With these factors presenting a favorable prospect, renewed efforts were made to remove the remaining objectionable features to the use of molybdenum. As a result of these efforts, the element, in three different forms, was soon procurable at a cost which made it possible to manufacture the molybdenum steels in competition with any of the other structural alloy steels of like grade and of similar properties.

Recent and Present Uses of Molybdenum Steels: With all barriers to its use removed, molybdenum steels were brought into extensive use during the last years of the war, and, it may be added, they served their

purpose well. One of the incidents in the use of molybdenum steel that attracted much attention during that time was in connection with high speed steel. In 1918 Prof. Arnold of Sheffield, England, produced a chrome-molybdenum-vanadium tool steel that removed more metal in machining tests than a chromium-tungsten-vanadium steel, and showed a cutting power superior to any other with which it was compared. The molybdenum content of this steel was approximately six per cent., while the tungsten content of the steel with which it was compared was approximately sixteen per cent. Since the composition of the two steels were otherwise almost identical, this comparison showed that 6 per cent. molybdenum is equivalent to 16 to 18 per cent. tungsten. But while these statements seem to indicate that molybdenum is an ideal element for producing high speed steel, it has one property which limits its use for this purpose. When steel with a high content of molybdenum, such as in high speed steels, is heated to the high temperature necessary for hardening these steels, the element on the surface is oxidized and the oxide sublimed, giving the tool a soft edge. In Arnolds' experiments, this soft metal was removed by grinding before the tools were put into service. With respect to the structural division, some of the molybdenum steels have found considerable favor among automobile manufacturers. Like the other structural alloy steels in this book, these structural molybdenum steels may be placed in two classes, namely, the ternary, or straight molybdenum, steels and the quarternary steels, in which the molybdenum is used in conjunction with some other alloying element. For convenience each class will here be considered separately.

Ternary Molybdenum Steels: The straight molybdenum, or carbon molybdenum, steels are not extensively used, because the full benefits of the molybdenum are not evident unless it is augmented by some other alloying element. The study of these steels is, therefore, of chief interest as a means of getting at the influence of molybdenum alone upon the physical properties and structural components of the steel. In these steels the carbon may vary as in the different grades of structural carbon steel, while the molybdenum content may range from .20 to 1.00 per cent. However, the straight carbon-molybdenum steels most often employed are of three types, as shown in the following table of analysis:

	Type 1	Type 2	Type 3
Carbon.....	.20 to .30 per cent.	.20 to .30 per cent.	.30 to .40 per cent.
Manganese.....	.50 to .80 per cent.	.50 to .80 per cent.	.50 to .80 per cent.
Phosphorus....	under .04 per cent.	under .04 per cent.	under .04 per cent.
Sulphur.....	under .05 per cent.	under .05 per cent.	under .05 per cent.
Molybdenum...	.25 to .50 per cent.	.50 to .75 per cent.	.75 to 1.00 per cent.

Effect of Molybdenum upon the Mechanical Properties of Steel: To determine the effect of Molybdenum alone a series of tests were carried

out on a representative electric heat of type 1, the data of which is shown in the following table:

Table 80. Physical Properties of Natural and Treated Carbon Molybdenum Steel.

Manner of Rolling: Cast into 18x21 ingots, reduced to 4″x4″ billets on two high blooming and three-high billet mills; reheated and rolled into ⅞″ rounds. Same care exercised as is usual with forging steel.

Selection of Samples: Two bars twenty feet long selected at random from the finished product. Four pieces ten inches long were cut from each end of each bar, and from these standard 2-inch test pieces were machined, after treatment, in the case of the bars heat treated.

Analysis: C. .24%; Mn. .69%; P. .008%; S. .020%; Si. .10%; Mo. .32%. Ladle and check analyses practically identical.

Speed of machine ¼″ per min. Elastic limit, or yield point, by drop of beam.

	HEAT TREATMENT		PHYSICAL PROPERTIES				
Bar and Test	Hardening, Degrees C.	Drawback in Lead, Deg. C	Tensile Strength	Elastic Limit	Elongation in 2 In., Per Cent.	Reduction of Area, Per Cent.	Izod Impact, Ft.—Lbs.
1a	As rolled		76,700	52,120	30.0	61.0	
2b	As rolled		71,570	50,620	29.5	58.9	21.0
3a	Annealed	at 870°	76,600	51,240	32.0	61.7	
4b	and cooled	in lime	70,800	46,860	31.5	60.3	17.7
5a	850°	Not	127,850	110,600	19.0	55.3	
6b	Quenched	drawn	125,800	108,000	18.0	53.7	23.5
7a	in water	450°	112,650	92,840	20.5	65.3	
8b		450°	114,150	92,840	20.0	66.5	92.5
9a		500°	107,900	87,900	20.5	65.5	
10b		500°	108,700	88,070	20.0	64.4	93.5
11a		550°	105,700	84,040	23.0	65.2	
12b		550°	106,400	85,770	24.5	67.1	102.5
13a		575°	100,550	81,100	22.5	67.8	
14b		575°	104,700	84,700	22.5	66.1	97.0
15a		600°	98,820	78,440	24.0	69.7	108.5
16b		600°	100,450	79,400	24.0	68.8	

If these results be compared with those for a carbon steel giving about the same tensile strength in the natural and annealed states as shown in table 70, it is seen that the addition of the molybdenum increases the tensile strength, the addition of .32 per cent. molybdenum being equivalent to about a ten-point increase in the carbon content; that the ratio of the elastic limit to the ultimate strength is raised somewhat; and that the ductility is benefited, the reduction in area being very materially increased. It is to be observed, also, that increasing the temperature of the drawback does not have the effect in lowering the elastic and the ultimate strength that such procedure has on carbon steels. This peculiarity of molybdenum steels is amply corroborated by other investigators. Other comparisons not shown in the table have also been made. The impact values for molybdenum steel in all conditions are far superior to those obtained for plain carbon or simple chrome steel, except that after quenching and drawing back at temperatures below 400°C., the impact values of molybdenum steel are liable to be no better than those of carbon steel. In case-hardening, molybdenum increases the rate of penetration of the carbon, and it is similar to chromium in this respect. In the hot working of this steel no benefits that can be attributed to the presence of molybdenum are observed, and many surface defects common in working plain carbon steel may appear in the molybdenum steel, also.

The Influence of Molybdenum Upon the Microstructure of Steel, its thermal critical points, and related subjects has been investigated by Leon Guillet in France, Thomas Swinden in England, and others in this country. The findings of these investigators may be summed up about as follows: In the absence of chromium or of manganese in excess of that usually added to carbon steels, the molybdenum, in natural steels, or steels that have been allowed to cool slowly from temperatures somewhat above the critical ranges, is found dissolved or diffused in the ferrite of the steel. In this respect it is similar to nickel, but unlike nickel, which remains uncombined and forms with iron a simple alloy at all temperatures, molybdenum apparently forms a compound with iron at temperatures a little above 800° C., which, with the cementite, dissolves in the austenitic metal. This molybdenum-iron compound does not readily separate from the solution, so that on slow cooling it causes a marked drop in the Ar. point. On rapid cooling, of course, it does not change at all and reverts to the normal state very slowly and completely only after being reheated repeatedly to 800° C. This hypothesis explains the high tensile properties maintained by these steels with the higher draw back temperatures. The amount the Ar. point is lowered depends upon the amount of molybdenum and carbon present and also upon the temperature from which the cooling is started. The presence of molybdenum also lowers the eutectoid ratio; with a molybdenum content of 8 per cent. and a carbon content of .40 per cent. there is no excess ferrite in the slowly cooled steel, and a special

microstructural constituent is formed which imparts to the steel a cementitic structure, as indicated in the constitutional diagram of Fig. 211, after Guillet.

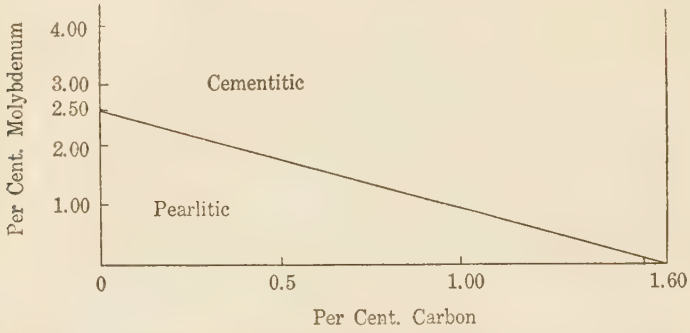


Fig. 211. Constitutional Diagram for Molybdenum Steel.—(by Guillet).

SECTION VIII.

THE QUARTERNARY MOLYBDENUM STEELS.

Effects of Molybdenum When Combined with Other Alloying Elements: As experience with other alloying elements would indicate and the results obtained by earlier investigators tended to prove, it was found, during the development of the molybdenum steels, that the benefits of the molybdenum are realized to the fullest when it is used in conjunction with one or more of the other alloying elements. Due to the pressing demand for the highest grades of steel at that time, feverish attempts to develop a super-steel were made. As the results that could be obtained with other elements were well known, the hopes of the experimenters were centered on molybdenum. The favorable results obtained with molybdenum in war materials served as an impetus to the post-war development of these steels, with the result that the element has been tried in almost every conceivable combination, and many different types of steel have been developed. All reports from these experiments and trials were favorable,—some so much so as to excite the suspicion that some of the claims for molybdenum steel might be attributable to over-enthusiasm. Consequently, during 1920-21, several series of experiments were carried out by the Carnegie Steel Company to determine what the actual benefits from molybdenum were. Space will not permit more than a statement of the conclusions that were made as a result of these experiments, and a tabulation of the results from the two most important series. In the first of these two series of experiments, a molybdenum and a chrome-molybdenum steel was each compared with a chrome and a plain carbon steel with a

view of determining the effect of molybdenum upon the mechanical and heat treating properties of steel. As considerable data on the straight molybdenum steels have already been given in Table 80, the results obtained with straight molybdenum steels are omitted in the following table:

Table 81. A Comparison of Carbon, Chrome, and Chrome-Molybdenum Steels.

Chemical Composition and Method of Manufacture:

	C.	Mn.	P.	S.	Si.	Cr.	Mo.
Carbon Steel—O. H.....	.45	.57	.012	.035	.04	...	...
Chrome Steel—Elec.....	.33	.41	.023	.029	.13	.72	...
Chrome-Molybdenum Steel—Elec...	.32	.72	.008	.030	.19	.80	.27

Size of Bars Used: Chrome Steel, 1⅛-inch rounds, others ⅞-inch rounds, all rolled in same manner and at approximately the same temperatures.

Sampling: 2 bars 20 ft. long, selected at random from each heat, were cut into 20-inch lengths, which were treated as shown in the table below.

Test Pieces: One test piece from each 20-inch length, turned, after treating, to the standard length and diameter for the 2-inch x .5-inch test piece. Impact tests were machined from prolongation left on the tensile test pieces.

Manner of Testing: Speed of testing machine, ¼-inch per minute, elastic limit by the drop of the beam. Four pieces for each grade and treatment were tested, and each value recorded in the table represents the average of the results obtained on the four pieces.

Table 81.—Continued.

KIND OF STEEL	HEAT TREATMENT		AVERAGE OF FOUR PHYSICAL TESTS					
	Hardening in Water, Deg. C.	Drawback in Lead, Deg. C.	Tensile Strength	Elastic Limit	Elongation in 2" %	Reduction in Area %	Brinell Number	Izod Impact, Ft.-Lbs.
Carbon.....	As rolled		82,075	50,100	28.3	48.8		16.5
Chrome....	As rolled		82,850	52,000	30.6	59.7		20.3
Cr.-Mo.....	As rolled		113,675	86,110	19.6	59.6	230	5.0
Carbon.....	Annealed in lime from	875°	77,075	41,900	28.1	44.9		10.5
Chrome....	Annealed in lime from	875°	78,200	46,745	28.9	52.6		15.3
Cr.-Mo.....	Annealed in lime from	860°	96,930	64,100	24.0	51.9	189	11.8
Carbon.....	860°	400°	127,350	100,450	12.3	33.5		27.3
Chrome....	845°	415°	138,500	118,140	12.7	39.4		10.5
Cr.-Mo.....	845°	400°	190,125	171,325	12.8	56.4	381	37.5
Carbon.....	860°	450°	117,775	81,750	13.0	35.4		29.0
Chrome....	845°	450°	133,350	98,755	14.7	45.7		14.5
Cr.-Mo.....	845°	450°	185,375	161,600	14.3	57.5	372	38.3
Carbon.....	860°	500°	114,650	81,150	16.5	42.1		26.5
Chrome....	845°	500°	127,400	99,755	16.8	51.0		21.0
Cr.-Mo.....	845°	500°	172,300	150,350	15.8	58.5	355	49.3
Carbon.....	860°	550°	107,225	74,400	19.8	47.0		27.5
Chrome....	845°	550°	115,450	93,530	20.6	61.2		78.0
Cr.-Mo.....	845°	550°	162,100	144,525	16.8	62.0	331	57.3
Carbon.....	860°	600°	101,325	70,500	22.8	54.9		30.0
Chrome....	845°	600°	109,250	87,495	22.1	64.6		85.0
Cr.-Mo.....	845°	610°	141,925	122,175	19.8	65.2	292	76.0

The object in the second series of experiments was to determine if the addition of molybdenum to forging steels imparted any properties advantageous in the mechanical working and shaping of such steels, or beneficial to them in service. To supply the materials with which to make the necessary comparison, five steels, a plain carbon, a simple chrome, a 3.5-per cent. nickel, a low nickel-chrome, and a chrome-molybdenum steel, each of a composition to give about the same tensile strength in the normalized condition after rolling were selected. The analyses of these steels are given in the subjoined Table No. 83. They were all made by the basic open hearth process, except the chrome-molybdenum, which was finished in the electric furnace. They were all rolled, preliminary to beginning the experiments, on the same mills and in the same manner into 4 x 4-inch

billets. To eliminate as many of the inherent defects as possible, a discard of 30 per cent. from the tops of the ingots was made, and the billets were pickled, inspected, and freed from surface defects by chipping. These billets were then subjected to the following comparative tests with the results as noted under each:

1. **Filling of passes in rolling:** Two billets from each heat were selected and rolled successively and under the same conditions on a 10-inch Belgian hand mill,—one billet from each heat into a ⅞-inch round and the other into a 1¼-inch round. After the bars had cooled to atmospheric temperature, they were carefully calipered. All five grades were found to vary in diameters to about the same extent.

2. **Tendency for surface defects to be rolled or forged out:** Two grooves ½-inch deep, one V-shaped and ½-inch across the top and the other oval-shaped and 2 inches across the top, were cut in a billet of each grade of steel. These billets were then rolled under the same conditions into 1¼-inch rounds. Upon examination, it was found that both grooves left seams in each bar, the V-shaped groove forming a deep seam and the oval-shaped groove forming a slight seam. The depth of the seams caused by the former varied from .12 inch in the nickel-chrome and chrome-molybdenum steels to .15 inch in the carbon steel, while the depth of the seams caused by the latter groove varied from .02 inch in the carbon and chrome steels to .05 inch in the nickel-chrome steel. A forging test was then carried out along similar lines. Two pieces 2½ inches long were cut from the ⅞-inch rounds rolled from each grade of steel. In one of these pieces from each grade a V-shaped groove, ¼ inch deep and ⅛ inch wide at the top, was cut longitudinally, and in the other piece from each grade a similar groove was cut transversely. These pieces were then heated to a forging temperature and upset under an air hammer to half their original length. On cooling, the grooves were carefully examined, but in no grade had they shown any tendency to disappear. Likewise, pickling tests upon several bars in each heat did not indicate that the surface condition of any one grade was superior to any other, very few defects, aside from a guide mark now and then, showing up in any grade. While these experiments may indicate that molybdenum is no aid to the elimination of seams after the defects that cause them have once been formed, the results cannot be taken as evidence against the correctness of the statements of a number of large users of steels of these grades that the molybdenum steels show fewer seams than the nickel steels.

3. **Formation of scale at rolling and forging temperatures:** Two bars 6 inches long from each grade of steel were carefully calipered at their centers, charged into an air furnace, and heated under conditions approximating those of a heating furnace, but out of contact with the flame, for two periods, one of a half hour and the other of five hours. At the end of

each period, the bars were allowed to cool, the scale was removed mechanically, and the bars were again calipered. Of the five grades the least loss in diameter due to scaling—.7 per cent. for the thirty-minute period and 1.0 per cent. for the five-hour period—was shown by the 3½-per cent. nickel steel, while the greatest loss,—2 per cent. for the 30-minute period and 3.8 per cent. for the 5-hour period—was shown by the chrome-molybdenum steel. It is to be noted, however, that whereas the scale on the chrome-molybdenum, as well as on the carbon and chrome steels, was easily detached, the scale on the nickel steel, and also to a less extent on the nickel-chrome steel, adhered very firmly to the surface. The adhesion of scale during the working of steel makes it very difficult to secure a good smooth finish on the bar or forging, for adhering scale is one of the most common causes of pits and rough surface marks. Therefore, the molybdenum steels are better working steels in this respect than the nickel steels.

4. **The hardness and resistance to deformation at rolling and forging temperatures** of the steels were compared at 1900° F. (1038° C.) and 2200° F. (1204° C.) by means of Brinell and compression tests. In the Brinell test, suitable test pieces freed from scale were subjected to a load of 2000 Kg. supported by a 1-inch ball, and the pressure was maintained for 15 seconds. For the compression tests, pieces three inches long were cut from the 1¼-inch rounds and machined to a diameter of 1.215 inches. These pieces were then heated in a muffle furnace to the required temperatures, placed in a tensile testing machine set up for compressions, and compressed at a speed of 3 inches per minute to a height of 1½ inches. The results of these tests are tabulated in the table below.

Table 82. Relative Hardness and Resistance to Compression of Forging Steels.

STEEL	Compression Tests Load to Compress a 3″x1.215″ Round to 1½″		Brinell Tests Load 2000 Kg. Dia. of Ball 1-Inch	
			Diameter of Impression	
	at 1900° F.	at 2200° F.	at 1900° F.	at 2200° F.
Carbon	31,800	16,950	.445	.540
Chrome	36,925	21,575	.420	.530
Nickel	38,825	21,000	.420	.525
Chrome-nickel	38,825	20,150	.420	.525
Chrome-molybdenum	51,100	26,625	.385	.515

While these tests show a greater resistance of the chrome molybdenum steel to deformation at these temperatures than any of the others, indicating that more power is required in forging and rolling this steel, they give no accurate indication of the relative flowing properties of the steels, such as the niceness with which they will fill the dies in drop forging.

5. **Ease of machining:** Threading and turning tests, approaching uniform laboratory conditions were made, in which it was attempted to indicate relatively the ease with which the different steels can be machined in terms of the power required to perform a definite amount of work. From the standpoint of reliable data, these experiments were disappointing, but the data obtained would indicate that the carbon steel is the easiest to machine, the chrome molybdenum is next, and that there is little difference among the other three. Reports from some machine shops are to the effect that tools show a much longer life when working with molybdenum steels than with nickel and chrome steels.

6. **The mechanical properties** of the steels were compared in the normalized and heat treated conditions, the composition and treatments being varied to give approximately the same tensile strength. The data collected are shown in the following table:

Table 83. A Comparison of the Mechanical Properties of Forging Steels.

Chemical Composition:

KIND OF STEEL	PER CENT. OF							
	C.	Mn.	P.	S.	Si.	Ni.	Cr.	Mo.
Carbon	.62	.45	.022	.041	...	....	...	...
Chrome	.49	.53	.025	.035	.02	....	.60	...
Nickel	.40	.65	.010	.035	.03	3.60	...	...
Chrome-Nickel	.43	.57	.012	.040	...	1.60	.46	...
Chrome-Molybdenum	.32	.72	.008	.030	.19	....	.80	.27

Size of Bars used, ⅞-inch rounds. All samples were machined to the standard sizes and shapes for testing after treatment. Bend tests were made on square bars ½″ x ½″ x 8″, notched in the center on one side to a ¼-inch in depth, which were then bent on supports 5 inches center to center to the beginning of fracture in a tensile test machine.

Table 83—Continued.

GRADE	HEAT TREATMENT			TENSILE TESTS				Brinell Number	Izod Impact	BEND TEST	
	Annealed Cooled in Air	Oil Quenched	Drawback	Tensile Strength	Elastic Limit	Elong. in 2″ %	Red. of Area %		Ft.—Lbs.	Load, Lbs.	Deg.
Carbon.....	775° C.			103,050	62,410	19.0	29.9	196			
Chrome.....	(1425° F.)			116,250	74,080	20.0	41.2	217			
Nickel.....	"			104,750	70,925	21.7	40.8	205			
Cr.-Ni.....	"			111,750	70,335	22.3	49.5	212			
Cr.-Mo.....	"			109,450	89,390	20.8	52.9	217			
Carbon.....	"	843° C.	565° C.	126,175	84,380	18.0	43.6	235	5.0	1225	15
Chrome..	"	(1550° F.)	610° C.	125,300	107,225	18.0	56.5	228	66.5	1300	25
Nickel.....	"	"	540° C.	127,975	112,525	18.8	51.4	248	54.5	1355	19
Cr.-Ni.....	"	"	600° C.	127,975	111,025	19.8	60.3	248	54.0	1320	22
Cr.-Mo.....	"	"	616° C.	125,650	112,250	21.0	68.0	235	90.0	1365	30

From these data it is evident that molybdenum has the effect of markedly increasing the ratio of the elastic limit to the ultimate strength as compared with carbon steel but only slightly so when compared with other alloy steels of similar mechanical properties, otherwise. In ductility, as shown in both the tensile and bend tests, the chrome-molybdenum steel is superior to all the others, while its ability to withstand impact, as indicated by the Izod test, is very remarkable. In all these features, these tests but corroborate the results obtained by a great number of other investigators.

7. **Structure:** While it has been claimed by some that the presence of molybdenum prevents the formation of a fibrous structure in heat treatment, it was found in experiments with these and plain molybdenum steels that all the steels containing molybdenum could be treated to develop a fibrous structure, as well as those containing nickel or chromium or both. A fibrous structure is very difficult to obtain in a plain carbon steel.

Types and Grades of Quarternary Molybdenum Steels: As previously stated, molybdenum has been tried out and used in combination with various other alloying elements. Thus, in the structural division, there are the nickel-molybdenum, the chrome-molybdenum, the chrome-nickel-molybdenum, the chrome-molybdenum-vanadium, the manganese-molybdenum, and the silico-manganese-molybdenum steels. Of these, the first two grades are of most importance for structural purposes and from the standpoint of tonnage used, and are, therefore, deserving of special mention here.

The Nickel-Molybdenum Steels are made in several different types, which may be classified as high nickel-molybdenum, containing about

3.00 per cent. nickel combined with .25 to .50 per cent. molybdenum, and the low nickel-molybdenum, in which the nickel content is about 1.50 per cent. and the molybdenum is varied from .25 to 1.00 per cent. to produce three types depending upon the molybdenum content. In none of these steels will the carbon content exceed .40 per cent. In all these steels the molybdenum may be considered as a worthy substitute for chromium in the chrome-nickel steels to which they are said by some to be superior in resistance to shock. In this connection the following table may profitably be studied in comparison with Tables 73, 76 and 83.

Table 84. Effect of Heat Treating upon the Static Mechanical Properties of a Low Nickel-Molybdenum Steel.

Chemical Composition: C. .39%; Mn. .45%; P. .039%; S. .027%; Si. .20%; Ni. 1.60%; Mo. .40%.

Description of Pieces Treated: One inch rounds, 29 inches long; 14 pieces all from same billet.

Test Pieces: One test piece from each of the 14 pieces treated, turned to a diameter of ½-inch, as in Fig. 47.

HEAT TREATMENT		PHYSICAL TESTS						
Hardening and Refining, Deg. C.	Draw, Deg. C.	Tensile Strength	Elastic Limit	Elong. in 2" %	Red. in Area %	Brinell Number	Sclero-scope Test	Charpy Impact
As rolled		119,000	88,000	18.0	38.8	262	34	10.17
Annealed and cooled in fce.	760°	98,000	62,000	23.5	43.0	187	28	8.08
Heated to 815° Quenched in oil	427°	190,000	171,000	12.5	46.0	352	49	12.93
	482°	180,000	160,000	13.0	44.0	352	50	15.24
	538°	185,000	163,000	16.5	45.4	363	48	17.06
	593°	150,000	138,000	16.0	49.7	321	46	18.95
	649°	115,000	100,000	25.0	59.6	241	35	27.09
	704°	100,000	71,000	26.0	47.1	201	30	11.79
Heated to 815° Quenched in water	427°	190,000	175,000	12.0	49.2	388	53	17.67
	482°	195,000	170,000	13.0	40.4	388	52	14.06
	538°	183,500	169,000	16.0	49.7	341	50	16.44
	593°	150,000	138,000	18.5	47.2	285	41	21.65
	649°	123,500	110,000	21.5	59.8	255	37	28.53
	704°	101,000	75,000	26.0	55.5	207	30	22.00

The Chrome-Molybdenum Steels: Of all the combinations in which molybdenum has been tried, the chromium-molybdenum, considered from the standpoint of cost and general utility, has been found to be the best.

The molybdenum in these steels appears to intensify the strength-giving capacity of the chromium, while at the same time it overcomes to a remarkable degree the tendency to brittleness that usually accompanies any increase of the tensile strength of steel, generally making it more ductile than any other steel with the same strength and always giving a remarkably higher impact test value. The quality indexes of the chrome-molybdenum steels are always much higher than that of any other alloy steels of structural grades. A study of the properties of these steels has led to the development of several different types which may be classified as low molybdenum, medium molybdenum and high molybdenum, in which the range in the molybdenum content is .25 to .50 per cent., .50 to .75 per cent., and .75 to 1.00 per cent., respectively, while the carbon content ranges from .10 to .50 per cent., and the chromium content is .70 to 1.00 per cent. in each. The low molybdenum type is the one most used, and it is made in four different grades or types; namely, one with a carbon content of .15 to .25 per cent., and a manganese content of .40 to .70 per cent. for case hardening; another, with a carbon content of .20 to .30 per cent., and a manganese content of .50 to .80 per cent., for either case hardening or oil quenching; a third, with a carbon content of .30 to .40 per cent. and a manganese content of .50 to .80 per cent., for purposes requiring heat treated steels; and a fourth, with a carbon content of .40 to .60 per cent. and a manganese content of .60 to .90 per cent., for springs. These steels are now being used by manufacturers of automobiles and tractors, agricultural implements and machinery, and they hold promise of becoming the most widely used of all the other alloy steels. From their merits now apparent, they may be used to a considerable extent as substitutes for 3½-per cent. nickel, straight chrome, chrome-nickel, and chrome vanadium steels. They can be manufactured as cheaply as any of these steels and more cheaply than some. In cases where the finish obtainable by forging or rolling is important, they have an advantage over the nickel steels, while the sensitiveness of the chrome-vanadium steels to heat treatment gives the chrome-molybdenum a decided advantage over them, too. No other alloy steels permit as wide a temperature range in heat treatment for either quenching or drawing back as the chrome-molybdenum do. Apparently, quenching temperatures ranging from 810° C. to 950° C. (1490° to 1742° F.) have comparatively little effect upon the static physical test properties of these steels. The following table may be studied for the effect of different draw back temperatures.

Table 85. Illustrating the Effect of Heat Treatment Upon the Mechanical Properties of Low Chrome-Molybdenum Steel.

Chemical Composition: C. .44%; Mn. .53%; P. .031%; S. .026%; Si. .26%; Cr. 1.06%; Mo. .35%.

Samples Treated: One inch rounds, 25 inches long, 14 pieces all from same billet.

HEAT TREATMENT		PHYSICAL TESTS						
Hardening and Refining, Deg. C.	Drawback, Deg. C.	Tensile Strength	Elastic Limit	Elong. in 2" %	Red. of Area %	Brinell Number	Scleroscope	Charpy Impact
As Rolled		145,000	106,000	15.0	31.5	297	38	5.61
Annealed at 760° and cooled in furnace		98,000	54,000	27.5	58.6	181	26	21.65
Heated to 815° Quenched in oil	427°	223,000	199,000	11.5	39.7	444	56	10.17
	482°	208,000	185,000	12.5	40.4	422	51	10.17
	538°	193,500	176,000	15.5	44.9	388	47	14.06
	593°	180,000	164,000	15.0	49.2	375	46	18.31
	649°	170,000	156,000	18.0	52.0	363	46	20.44
	704°	112,000	95,000	25.0	65.1	235	36	36.15
Heated to 815° Quenched in water	427°	225,000	198,000	11.0	42.5	444	63	10.71
	482°	200,000	179,000	13.0	38.9	415	56	13.49
	538°	200,000	183,000	18.0	53.9	375	50	20.44
	593°	183,500	170,000	21.0	59.8	302	45	28.53
	649°	124,000	103,000	23.0	63.7	269	38	35.38
	704°	94,000	65,000	33.5	69.9	187	29	49.40

The Manufacture of Molybdenum Steels offers no difficulties that cannot be overcome by the exercise of the usual care given to the manufacture of other alloy steels. These steels are made by the crucible, the electric, and either the acid or basic open hearth processes. The element is obtainable in three forms, namely, as amorphous metal, as ferro-molybdenum which contains preferably from 50 to 60 per cent. of molybdenum, and as calcium molybdate, which has a molybdenum content of about 40 per cent. The amorphous metal is the least desirable because of its high melting point and its powder-like form. In the crucible and electric processes the ferro-molybdenum is preferable, and is added near the top of the charge in the case of the former and at any time during the reducing period in the case of the latter. In the open hearth processes either the ferro-molybdenum or the calcium molybdate are available, and may be added to the metal any time after the scrap has melted or the hot metal has been charged. Once the element has dissolved in the metal of the bath, there is little danger of loss due to oxidation. Molybdenum steel scrap may, therefore, be employed to supply a part of the molybdenum required by the heat. In case no molybdenum scrap is used, it is customary,

for various operating reasons, to delay the addition of the molybdenum until the working period has well advanced, adding the molybdenum just long enough before tapping the heat to permit of its becoming thoroughly diffused throughout the bath. In spite of the fact that apparently there is no loss of molybdenum in melting down molybdenum steel scrap, when ferro-molybdenum is added to the bath, even in containers, and at the time mentioned above, there is a loss of approximately 10 per cent. of the molybdenum, yet none of this metal is found in the slag. This loss is probably explained by the fact that at temperatures above 600° C. the element is rapidly oxidized in an oxidizing atmosphere to the trioxide, MoO_3, which immediately sublimes at the temperature of formation. This loss, or a large part of it, is said to be avoidable by the use of calcium molybdate.

SECTION IX.

MANGANESE STEEL.

General Characteristics of Manganese Steels: The beneficial effects of manganese when added to steel in small amounts, corresponding to .25 to 1.00 per cent., have already been discussed. Early in the history of the use of the element in steel, it was observed that increasing the manganese content above .60 to .80 per cent. caused the steel to become proportionally harder and stronger until, with a content of about 3.00 per cent., the steel was so brittle that it was thought metal containing a greater proportion of manganese would be useless. That this idea was totally erroneous was first shown by Robert A. Hadfield in a paper on manganese steel read before the British Iron and Steel Institute in 1888. He found that while steel containing from 3 to 7 per cent. of manganese was "practically as brittle as glass," steel containing from 7 to 20 per cent. manganese could, by proper treatment, be made very tough and strong. Besides, these alloys exhibited peculiarly distinctive properties. Hadfield's work showed that, with a carbon content of .80 to 1.30 per cent., a manganese content of 10.00 to 15.00 per cent. gave steels in which the beneficial effects of the manganese were realized to the fullest extent. With a lower carbon content more manganese would be required. As the steel was made by the addition of ferro-manganese to decarbonized iron, and as blast furnace ferro-manganese was the only grade of this material available, the high carbon content could not in practice be avoided.

Composition of Manganese Steels: To the alloys covered by his patents, namely, steel containing from 7 to 30 per cent. manganese, Hadfield applied the term manganese steel. But, since the alloy containing 11 to 14 per cent. manganese was the strongest and most ductile, that is, the toughest that could be made with ordinary ferro-manganese, hence the

composition most used, the term came to be restricted to this one alloy. With this proportion of manganese added in this form the other elements present ordinarily fall within the following limits: Carbon 1.00 to 1.30 per cent.; phosphorus .05 to .08 per cent.; sulphur under .03 per cent.; silicon .20 to .50 per cent. This is the composition that can be expected when manganese steel is ordered merely by name, or when no specifications are given. In honor of the discoverer, this steel came to be called, and is yet frequently designated as, Hadfield steel. On account of their lower cost, attempts have been made to substitute for the regular grade of manganese steel the alloys containing from 7 to 10 per cent. manganese, but their use is restricted on account of their greater brittleness. As a commercial name for these steels, the term "loman steel," an abbreviated form for low manganese steel, has been suggested.

The Three Classes of Manganese Steel: The properties of these manganese steels can be most briefly discussed and most readily understood, perhaps, by immediately referring to Guillet's constitutional diagram for these alloys. From this diagram it will be seen that in the case of pure,

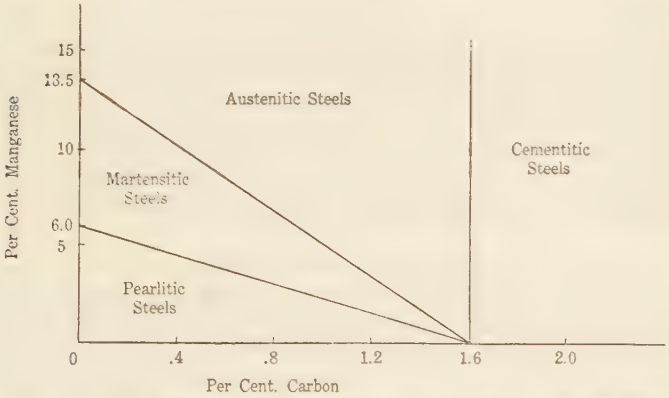


FIG. 212. Constitutional Diagram for Manganese Steel.—(by Guillet).

or carbonless, iron cooled slowly, a manganese content under 6 per cent. gives a pearlitic structure; between 6 and 13.5 per cent., a martensitic structure; and above 13.5 per cent., an austenitic structure. As the carbon is increased, less and less manganese is required to impart these different structures. For example, with a carbon content of 1 per cent., only about 2.5 per cent. manganese would be necessary to give a martensitic structure, while 7 per cent. would give an austenitic structure.

The Pearlitic Manganese Steels: The higher manganese pearlitic steels have not received much attention, possibly because of Hadfield's original statement that the alloys between 2 and 6 per cent. manganese

were hopelessly brittle. It has been shown since, however, that if the carbon content is low, these steels are much stronger than ordinary steel, and almost as ductile, when cooled slowly through the critical range. Laboratory tests indicate they should compare favorably with nickel steel except that they are much more sensitive to quick temperature change. For some purposes, these steels, if properly treated, have been found to render better service than any others. Thus, for example, steels containing from 1.50 to 2.25 per cent. manganese and from .40 to .60 per cent. carbon give, after being quenched in oil and drawn within their hardening range, best service for shear blades. They may also be used for various parts of machines and have been used with entire satisfaction in automobile construction as a substitute for other alloy steels, such as low nickel-chrome steel. Manganese in similar proportions is used to produce the non deforming steels to be described in the next chapter. When these steels are quenched to atmospheric temperatures, especially with water as a medium, unstable martensite is formed at the outer surface while stable martensite or troostite is formed at the inner or central portions, which fact, due to the subsequent contraction of the outer part, causes the steel to crack at the surface.

Martensitic Manganese Steels: As would be expected, all the martensitic manganese steels are brittle. This property, however, reaches a maximum in alloys bearing 3.50 to 5.00 per cent. manganese and .30 per cent. or more of carbon. When the manganese content is increased above 5.00 per cent. the brittleness decreases slightly until at about 7.00 per cent. the alloys are ductile enough to use for certain purposes where great hardness and little strength and resistance to shock are required.

Mechanical Properties of Austenitic Manganese Steel: It will now be evident that the alloys commercially known as manganese steel, containing about 13.00 per cent. manganese and 1.00 per cent. or slightly more of carbon, are austenitic. Its properties, therefore, are those of austenite and are very distinctive as compared with ordinary steel. In the raw condition, after casting, it is comparatively weak. The elastic limit is low, and sometimes can scarcely be detected on the ordinary testing machine; the tensile strength varies from 85,000 to 100,000 pounds and the elongation from 2 to 6 per cent. in 8 inches, while the reduction in area is about 8 per cent. Hence the metal offers little resistance to shock. Hot working improves the physical properties a little, but reheating the metal to 1000°C. (1832°F.) and quenching, preferably in water, produces a marked improvement in all these properties. The tensile strength is increased to between 140,000 and 150,000 pounds; the elastic limit to between 33 and 50 per cent. of the tensile strength; the elongation to 45 or 50 per cent. in 8 inches; and the reduction of area to between 30 and 40 per cent. Besides, this treatment imparts a peculiar tough-like hardness, which, though the metal can be marked with a file and the Brinell number is only about

175 (it varies from 160 to 190, thus corresponding to a .50 carbon untreated plain steel), makes the steel very difficult to machine even with the best of tools. The low elastic limit and Brinell number indicate what for certain purposes constitutes a fault in the metal, namely, its tendency to flow under static stresses or repeated blows. Lacking elasticity, a lack characteristic of austenite, the metal cannot recover its shape when once deformed, even though the deformation may be very small. However, cold working increases the hardness of the metal very rapidly, which fact explains its remarkable resistance to wear.

Cause of the Change in Properties on Quenching: The reason for the great increase in toughness of the metal produced by quenching is revealed in part by the microscope. In a paper read before the British Iron and Steel Institute in 1910, Arnold and Read showed that manganese steels slowly cooled contained iron and manganese carbides, Fe_3C and Mn_3C. Under conditions of slow cooling, these carbides segregate, and can be seen under the microscope as a net work surrounding the crystals of austenite. The continuity of the austenite being thus completely interrupted, the properties of the metal must partake largely of the nature of these carbides, which are very hard and brittle. In reheated and quenched specimens, provided they have been heated to a sufficiently high temperature, no trace of these carbides can be detected with the microscope. The reheating either causes these carbides to become diffused in the austenite or decomposes them into their elements, which alloy with and diffuse or dissolve in the metal. Quick cooling causes them to remain in solution, or in a state of diffusion beyond the resolving power of the microscope; or, for lack of time, prevents their formation, in which case water toughened manganese steel would be a solid solution of carbon and manganese in austenite.

Other Properties: Among its other interesting properties, water toughened manganese steel is practically non-magnetic, which is also to be expected from its austenitic structure. It is a much poorer conductor of heat and electricity than ordinary steel; its electrical resistance is 25 to 30 times that of copper. Its coefficient of expansion is also higher than carbon steel, a matter of great importance when using it for castings. Cold working increases the strength of toughened manganese steel and destroys its ductility, as in the case of ordinary carbon steel, but the increase of strength for a given amount of deformation is somewhat greater. Thus, in pulling a test, the piece does not "neck" down at the point of rupture to the same extent carbon steel does, but tends to stretch more nearly uniformly throughout its length. This fact accounts for the low reduction of area which is always less than the elongation, and also explains why the elongation in 2 inches is sometimes nearly the same as in 8 inches.

Uses of Manganese Steel: This recitation of the properties of manganese steel is to indicate new uses to which the steel may be successfully

applied, for such a study shows clearly that, while this steel may be peculiarly fitted for some purposes, it is totally unsuited for others. As a further aid in determining to what kind of service the steel is best adapted, some of the uses to which it has been successfully applied will be given. One of the fields in which it has proved most serviceable is that covering frogs, switches, crossings, curved rails and cross-overs for railroad and street car tracks. In railroad service, manganese steel curved rails will last 5 or 6 times as long as ordinary steel, while in street car tracks it gives even better service. In building mining, milling, rock crushing, digging and dredging machines, it is used to form those parts subjected to abrasion or unusual wear. In certain high speed impact machines, however, the use of the metal has proved disappointing because of its tendency to flow, when such conditions as these are imposed upon it. Also, when the parts require a great deal of machining, the cost of grinding manganese steel to size may prohibit its use. The great hardness of the metal, or its resistance to being cut, combined with its great toughness, makes it particularly well adapted to the construction of burglar proof safes and vaults. Its most remarkable performance is to be seen in screening coke. This substance has a peculiar cutting effect upon screens made of other metals,—an effect out of all proportion to the magnitude of the impacts—but the abrasion is comparatively very slight in the case of screens made of manganese steel. The non-magnetic property of the metal makes it suitable for the structural parts of certain magnetic instruments, such as ships compasses and lifting magnets, also for various parts of electrical machines where before only brass or some other soft metal was available.

Making Manganese Steel: Until recently, manganese steel was always made, commercially at least, by mixing molten ferro-manganese with purified decarbonized metal in a ladle. Since the proportion of ferro-manganese to molten iron is large, about 1 to 5, the ferro-manganese cannot be added in the ladle in solid form, because it would lower the temperature of the steel too much; and it cannot be added in the open hearth or Bessemer furnaces on account of the large loss from oxidation. For melting the ferro-manganese, cupolas have been tried, but this method is economically impracticable on account of the unavoidable losses of manganese through oxidation and slagging. Hence, this part of the process must be carried out in the crucible or the electric furnace, in either of which the loss of manganese is very small. In case crucibles are used, the furnace, as well as the crucibles, is similar to that employed in the manufacture of crucible steel. The crucibles are of graphite and are charged and fired in the usual way. Ferro-manganese melts at a much lower temperature than steel, and, being saturated with carbon, it does not attack the crucibles by absorbing carbon from them. It requires about 2 hours to melt a charge, and the life of the crucibles is from 8 to 12 heats. Where conditions are favorable, it is probable that the electric furnace will eventually replace the crucible process for this purpose.

The Decarbonized Iron may be obtained by any of the purification processes, but the process most favored is that of the acid open hearth. This process requires high grade pig iron and scrap, but it is the one best adapted to a plant manufacturing manganese steel exclusively, because it is the most flexible, and most easily controlled. The operation of the furnace and the process does not differ from the usual practice except that the heat is tapped without the usual deoxidizing and recarburizing additions. Care is exercised, of course, to see that the metal is not too hot or too cold and the slag does not contain any excess of oxides. The composition of the metal as tapped should be as follows: The carbon should be under .10 per cent., and the phosphorus under .04 per cent. The percentages of silicon and manganese will, of course, have been reduced to the usual points for decarbonized metal. While precautions will be taken to keep the sulphur within reasonable limits, its percentage does not need to be as low as that of the phosphorus, because it is largely eliminated through action of the manganese after the ferro and iron have been mixed.

Mixing the Ferro and Decarbonized Metal: With the charge in the steel furnace about ready to tap, the crucibles are removed from the melting holes and their contents poured into a large fire clay lined mixing ladle, which has been previously dried and warmed with a gas jet in the usual manner. The size of this ladle will depend upon the size of the charge, and its form upon the method of disposal of the finished steel. If the steel is to be cast into ingots, it will be provided with teeming nozzle and stopper, and resemble the ordinary steel ladle; but if the steel is to be used for castings, the ladle will be of the lip-pouring type. These casting ladles are frequently constructed on the coffee pot principle, that is, they are provided with a plate, fastened edge up just back of the lip, to act as a skimmer to prevent the slag that invariably forms and floats on the surface of the steel from getting into the casting. As soon as all the molten ferro-manganese has been transferred to the ladle, which seldom requires more than five minutes, the ladle containing the decarbonized metal is carried by overhead crane, or other means, and suspended over the mixing ladle, when its metallic contents is teemed into the molten ferro-manganese. This procedure prevents the purifying furnace slag, which would otherwise oxidize a large and variable amount of the manganese, from flowing into the mixing ladle. After mixing, it is advisable to allow the steel to stand in the ladle a few minutes in order to give the manganese oxide and sulphide formed a chance to rise to the surface of the steel. A little manganese silicate may also be formed through action between oxides in the molten iron and silicon in the ferro or through reaction of manganese oxide with the lining of the ladle. But care must be exercised to see that the steel does not get too cold, especially if it is to be used for castings.

Loss of Manganese: These reactions in the ladle result in a loss of manganese in the metal. This loss may vary considerably, being affected

by the method used for decarbonizing the iron,—more particularly the quantity of oxides and sulphur the metal contains—and also the method of melting the ferro-manganese. When the acid open hearth process is used for decarbonized metal, and the electric furnace for melting the ferro-manganese, this loss will amount to about 2 per cent. of the manganese added; when the ferro is melted in crucibles the loss may be kept under 1 per cent. The theoretical amount of ferro-manganese required must, therefore, be increased proportionally for each method, and the exact factor must be determined by experience for each case. Provision must be made, of course, for obtaining the weights of both the decarbonized iron and the ferro-manganese. With the acid open hearth or the electric furnace, the weight of the former may be estimated from the charge, but with the Bessemer converter the mixing ladle should be mounted upon a scale platform, which provides a means of weighing both the ferro-manganese and the decarbonized iron.

The Use of Electric Furnaces for making manganese steel has not been thoroughly tried out on a commercial scale, but where electrical power is cheap and other conditions are favorable, the electric furnace would seem to offer the ideal method for the production of this steel. It would permit the use of either pig iron or scrap alone or a mixture of these two, and the manganese could be added without loss to the iron in the furnace. By the use of a basic lined furnace and an initial oxidizing slag, the silicon, sulphur, manganese, phosphorus, and carbon could be reduced in amount to low limits, when, by raking off this slag, the ferro-manganese could be added under a reducing slag and the steel finished in the furnace. Under the conditions prevailing at present in most steel-making localities, however, the increased cost of the electric process over the older processes would probably more than outweigh any metallurgical advantages of the former.

Shaping the Steel: The first manganese steel used was forged, but later it was found that, if the steel was properly made and poured, it would always give perfectly sound castings, and this method of shaping came to be used wherever possible because it is the cheapest. Besides, many of the articles for which manganese steel is used can not be made in one piece by forging or rolling only. On the other hand, some articles, like rails and certain parts of machines, are most readily made by rolling or forging, and in such cases the cheaper method will be used, of course. On account of its higher coefficient of contraction, articles of manganese steel cannot always be rolled with the same rolls used for plain steel, and, in casting, a greater allowance for shrinkage must be made, the usual factor for the dimensions of the mould being 1.026 times the linear dimensions of the casting desired. The metal is usually cast in sand moulds, either green or dry, but where conditions require it, metal moulds may be used.

Heat Treatment: As previously indicated, the toughening of the steel is effected by heating the material uniformly to a temperature of about 1000°C. and quenching in water. In practice, a range of temperature from 1750°F. to 1850°F. is usually permitted. Since water is the most rapid cooling agent of all the other commercial quenching media, it gives the best results because it prevents most efficiently the separation of iron and manganese carbides, which tend to make the steel weak and brittle. Because the metal is a poor conductor of heat, and has a high coefficient of expansion, it must be heated slowly and should be charged into a cold furnace, or one but slightly hotter than the steel itself, else the rapid rise in temperature and consequent expansion of the outer portions may rupture the central portion. The same properties of the metal make it unsafe to quench the steel from the original heat of the casting, rolling or forging. Though such a procedure would seem feasible from a theoretical point of view, it is not permissible in practice, for, since the thin portions are cooler than the heavier parts to start with, sections are liable to be cracked by the unequal rates of contraction brought about by the cooling. Castings should be allowed to cool almost to atmospheric temperatures in the moulds, then they should be cleaned of adhering sand, and the runners and sink heads should be removed before treating. The cleaning is done with pneumatic hammers and sand blasts, while the runners and sink heads may be burned off with the oxyacetylene torch.

Straightening and Finishing: The quenching usually causes the article to warp. In some cases this warping is very pronounced and cannot be avoided. However, as the steel is very ductile and has a comparatively low elastic limit, most articles can be readily straightened by means of the gag press. The amount of the distortion may be greater without the danger of injuring the article by cracking than in the case of high carbon plain steel, because the metal is more plastic. The metal must not be heated for straightening or for any other purpose, as reheating after quenching causes the carbides to segregate again and makes the metal brittle. This is an important point to bear in mind when putting the steel into service. After straightening, the article is ready for machining, all of which, on account of the great toughness of the metal, must be done by grinding.

SECTION X.

SILICON STEEL.

Occurrence of Silicon in Steel: From the descriptions given in other parts of this book, it is evident that some silicon will be found in practically all kinds and grades of iron and steel. Silicon is a constituent of all pig iron, and its complete removal from the metal by any of the commercial methods of purification is very difficult. In ordinary practice, therefore, some will remain as residual silicon, the amount of which will depend upon the raw materials used, the method of making the steel, and the manner in which the heat was handled. In general, this residual silicon is lowest in basic processes and highest in acid processes. For example, in the basic open hearth process, the residual silicon will seldom exceed .02 per cent., while in the acid open hearth it may range from .03 to .25. In properly blown acid Bessemer steel, the residual silicon is very low, under .02 per cent., but a much higher content may be obtained if the heat is blown too hot. In the electric process, silicon is removed only when an oxidizing slag is employed; if the metal is treated under a reducing slag, no silicon is removed, in which case the silicon content of the steel depends upon the raw materials. Crucible steel always contains silicon, which is derived from the charge and from the walls of the crucible, if these were made of graphite and clay. In addition to this residual silicon, some silicon is introduced through the recarburizing and deoxidizing agents employed in finishing the heat, and some may be intentionally added to any of these steels for curative purposes, the proportion so added varying from .05 to .50 per cent. Hence, by composition alone, it is impossible to distinguish silicon treated steel from untreated steel.

Silicon Alloy Steel Defined: Similarly, no sharp distinction between silicon treated and silicon alloy steels can be made, because silicon, unlike most of the other alloying elements used in steel does not produce any marked or sudden changes in the mechanical properties, nor does it produce any change in the structural constituents of the steel, until the silicon content is raised to 4 or 5 per cent. Likewise, custom is no guide in this case. For curative purposes the amount employed will seldom exceed .50 per cent., but larger amounts may be used occasionally. So far, silicon has been used to produce only two types of ternary structural steels, namely, one commonly known in the trade as electrical sheet and another as silico-manganese steel. In these the silicon content of the former varies, according to grade, from about 1.00 per cent. to 4.50 per cent., while the silicon content of the latter usually varies from 1.00 to 1.50 per cent., but is sometimes less than 1.00 per cent. Therefore, since silicon treated steels may contain more than .50 per cent. silicon, and silicon alloy steels may contain as little as .50 per cent., the nearest custom comes to supplying a definition for silicon steels is to say that no steel containing only silicon,

in addition to the carbon and manganese usually present in carbon steels, is to be considered as an alloy, or a special, steel unless the silicon content exceeds .50 per cent.

Effects of Silicon in Steel: The effects of silicon, upon the mechanical properties of the metal have been given in Chapter III (Part III), and although the discussion there referred mainly to simple steel and to silicon treated steels, the same remarks will apply to the useful silicon alloy steels. Concerning the effects of silicon upon the other physical properties and the chemical properties of iron, these may be summarized about as follows: Silicon lowers the coefficient of expansion of the steel somewhat; increases its electrical resistance; either increases or decreases its magnetic permeability, depending on the strength of the magnetizing force; and raises somewhat the power of the metal to resist corrosion. Its effects upon the critical points and upon the structural constituents of the

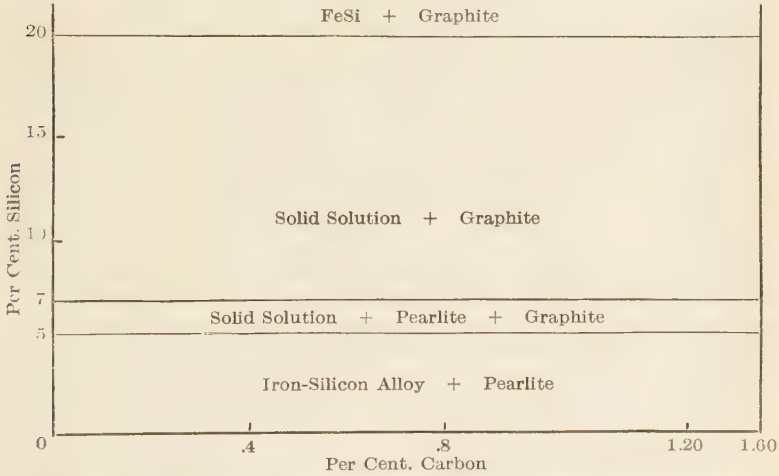


Fig. 213. Constitutional Diagram of Silicon Steel. (After Guillet, modified)

steel can be more definitely stated. Thus, F. L. Meacham[1], experimenting with steels containing .10 to 1.30 per cent. carbon, reports that, for each per cent. of silicon contained by the steel, the Ac_1 point is raised 28.1° C., and the Ar_1 point, on slow cooling, is raised 28.9° C.; and that silicon diminishes the intensity of the A_3 points very rapidly. According to Guillet's constitutional diagram, which is similar to that shown in Fig. 213, the structure of silicon steels, after cooling moderately slowly, is practically independent of the carbon content, and remains pearlitic until the silicon content exceeds 5 per cent., when some graphite is formed.

[1]See "The Effect of Silicon on the Thermal Critical Points of Steel", by F. L. Meacham, Trans. American Society for Steel Treating, Vol. 4, November, 1923.

The proportion of the carbon precipitated as graphite rapidly increases as the silicon content is raised to about 7 per cent., when all the carbon in the steel occurs as graphite. These facts explain why the silicon steels utilized so far contain less than 5 per cent. silicon. This diagram, however, does not present a true picture for all conditions, because in very low carbon annealed steels it is seldom that graphite can be detected with the microscope until the silicon content reaches 7 per cent., while in very high carbon steels annealing under certain conditions will produce some graphite with the silicon content as low as .5 per cent.

Nature of the Silicon-Iron Alloy: Although silicon can be made to combine with carbon to form the carbide SiC, it is certain no such combination takes place in steel, because the carbide is formed only at very high temperatures, much above the fusion point of iron or steel, and the effects produced by silicon in steel give strong evidence against such a combination. Alloying elements that form carbides with the carbon in steel increase its ability to absorb carbon, whereas silicon not only opposes the absorption of carbon but tends to precipitate that already present in the steel as graphite. Undoubtedly, then, the silicon is alloyed with the iron. As to the exact nature of this alloy there is room for much difference of opinion. According to some authorities silicon unites with iron to form the silicide, FeSi, which then forms a solid solution with the free iron in the steel, and up to 1922 this theory was generally accepted. Recently, however, some investigators working with the X-Ray spectroscope claim to have found that in some crystalline substances formerly considered stable chemical compounds, the atoms are not really in molecular combination, but are dispersed in accordance with a definite pattern as in the case of crystals of elementary substances, the different kinds of atoms occurring in a definite order. Therefore, it may be that silicon dissolves in gamma iron and remains in solution in alpha iron, dispersed, not as molecules of a chemical compound, but as atoms of the element.

Kinds and Uses of Silicon Steel: While silicon is used in varying proportions with other alloying elements to produce several different kinds and grades of special steels, there are, as already stated, only two types of structural silicon steels. The use of the name silico-manganese steel can scarcely be justified, because this steel seldom contains more than .70 per cent. manganese. The chief use of this steel is for springs of the leaf type, though it has also been used for gears. The silicon is said to impart greater resiliency and toughness to springs than can be obtained with plain carbon steel. For these purposes, a carbon content of .45 to .55 per cent.; silicon, 1.25 to 1.50 per cent.; and manganese .50 to .70 per cent. is usually specified. The second type, designated as electrical steel, is utilized, mainly in sheet form, in the construction of those parts of electrical apparatus, such as transformer cores, and the poles of motors and dynamos, that demand a high magnetic permeability and

electrical resistance for greatest efficiency. High magnetic permeability is desirable in steel used for these purposes because it reduces the strength of the magnetizing force required to produce any given intensity of the induced magnetism, and thus saves both material and energy. A high electrical resistance is desirable, mainly, because it aids in reducing eddy currents. Eddy currents are the electrical currents set up in the cores of transformers, generators, and motors because of the variations in the magnetic fields. In practice these currents are reduced by using metal with a high resistance and by building up the cores of thin sheets lightly insulated from each other and placed to lie in a direction at right angles to the direction of flow. Silicon, then, reduces the hysteresis loss and the eddy current loss, both of which together constitute the "iron" or "core" loss, and although other alloying elements may give similar results, none can be used to obtain the same results at as low a cost.

Factors Affecting the Efficiency of Electrical Steel: The factors that affect the magnetic properties of steel are the same as those affecting the mechanical properties, namely, composition, mechanical working, and heat treatment. As to the composition of silicon electrical steel, the carbon, manganese, phosphorus and sulphur contents should all be as low as possible, while the silicon content should be about 4.25 per cent. for the best results in transformer work. A specimen of sheets said to be most suitable for transformer cores gave the following results on analysis; carbon .07 per cent., manganese .09 per cent., phosphorus .012 per cent., sulphur .020 per cent., and silicon 4.28 per cent. With weak magnetizing forces, the permeability of this steel is greater than that of pure iron and the iron loss is said to be considerably less than that of any other alloy steel that can be produced at as low a cost. As the magnetizing force is increased the permeability decreases, until, with a strong magnetizing force, the permeability is less than that of pure iron. Some dynamo and motor work requires a lower silicon content than transformer steel, so that there are three or four different grades, known as high, medium high, medium and low silicon sheets. Also, since the efficiency of the steel used for these purposes is affected by the mechanical working and heat treatment, the quality of the steel does not depend entirely upon chemical composition, and these factors give rise to other grades. In general, any kind of cold working is injurious to the magnetic properties of the steel, and, of all the heat treatments that may be applied, annealing at temperatures between 600° and 900° C., gives the best results.

The Manufacture of Silicon Steel requires considerable care and not a few modifications of the usual practice followed in producing carbon and alloy treated steels. The silico-manganese steels may be made by either the acid or basic open hearth processes, with little deviation from the usual practice, but, to obtain the low sulphur and phosphorus content, the best grades of electrical steel are produced only by the basic open hearth process. With this process the almost complete elimination of the phos-

phorus, manganese and carbon presents no difficulty, but the exceedingly low sulphur content can be obtained only by the most careful selection of all raw materials and fuel or by special treatment of the metal in the furnace during the finishing period. This treatment usually involves a change of slags, the addition of a specially good grade of pig iron, and the holding of the heat in the furnace for an extra period at elevated temperatures. The addition of the large amount of ferro-silicon required also presents some difficulties, for if the alloy is added to the metal in the furnace, the silicon is oxidized rapidly, and, whatever the method of adding this alloy, the high silicon content is liable to cause the reduction of manganese and phosphorus compounds in the slag, which will contaminate the metal. After the heat is cast, the silicon prevents the formation of blow holes, but increases the size of the pipe in the ingot to a great extent. Consequently special precautions must be taken to overcome this defect. The heating and rolling of the ingots present no unusual difficulties, if the steel was properly made, but require, nevertheless, considerable care. The chief difficulties are encountered in rolling the sheet bar into sheets, and in annealing the sheets so that they will give the highest efficiency in service. These processes involve so many operations, and a satisfactory description of them would require so much detail, that it is inadvisable to attempt to follow them here.

CHAPTER V.

EXTRA-FINE TOOL AND SPECIAL STEELS.[1]

SECTION I.

QUALITY, GRADES AND KINDS OF STEEL.

Terms Used: In this chapter it is our purpose to discuss briefly those steels in which, on account of the uses to which they are applied, quality must be the first, if not the only, consideration. As the modifying terms used in the title to the chapter have not hitherto been generally applied to these classes or grades of steel, an explanation is desirable to indicate what these terms embrace. The word extra-fine indicates clearly enough superior quality, but what the other two adjectives may embrace is not so obvious. Originally the word tool was applied to any instrument, manually manipulated, that was used to facilitate mechanical operations, as a hammer, saw, chisel, etc., but as the field of man's activities was enlarged, the meaning of the word was broadened to include any hand operated implement or object used in performing any operation or carrying on work of any kind. When the implement or object is operated by machinery, it is designated as a machine tool. From these definitions it is evident the word tool embraces a great number of implements, which are required to perform work differing widely in character. The steels from which these implements are made must differ in properties, hence the term tool steel embraces many kinds and grades of steel. Parts of a machine itself are not referred to as tools nor is the steel used in the construction of such parts referred to as tool steel, though for many of these parts the steel should be of as high quality and in some cases even of the same composition as that used in tools. Steels intended for such purposes have hitherto been classed as structural steels. Again there are many other fields that require steel of special kinds or grades. Examples of such steels are those used for fine ball bearings, roller bearings, permanent magnets, valves of internal combustion engines, and the non-corroding steels used for high grade cutlery, pumps, etc. It is steels used for these and similar purposes that we here designate as extra-fine tool and special steels. These desig-

[1] For assistance rendered in the preparation of this chapter, the authors are especially indebted to Roy C. McKenna, President, and J. P. Gill, Metallurgist, of the Vanadium-Alloys Steel Co.

nations have not been generally used in this sense in the past. Special steel is a term that has been applied to alloy steels in general, and is also a term commonly used by the men in the mills to designate any steel made for a special purpose, or, in fact, any steel that may happen to differ markedly from the regular output of the mill.

Use of Term Crucible Steel to Designate Fine Steel: From the time of its introduction in 1742, the crucible process was used to produce the finest steels, and, up to the time of the adaptation of electric furnaces to steel making, about 1890, it was the only process available for the production of such steels. Hence the term crucible steel became synonymous of fine steel. Since 1910, however, many manufacturers of crucible steel have adopted the electric furnace to replace the crucible, but on account of the long standing of the term have been loath to surrender the name crucible steel as a designation for their products, because, aside from the method of melting, they have retained all the features of crucible steel practice, which is essentially a hand-craft practice, and the product of the new process is of the same or of even better quality.

Inherent Factors Determining Quality of Steel: By quality is meant the excellence or superiority of a certain steel for a given purpose or purposes. No steel has yet been discovered that could be made equally suitable to all purposes for which steel is used. Heretofore, so much emphasis has been given to the effects of methods of manufacture upon, and the relations of chemical composition and mechanical properties to, the quality that we are in danger of losing sight of the fact that the fundamental factors controlling the quality are to be found in the steel itself. These inherent factors that determine the quality of steel are:

I. **Chemical composition,** which implies the presence of the proper elements in correct proportions to impart the properties desired and the absence, or presence in negligible amounts, of elements injurious to the steel when used for the purposes for which the steel is intended.

II. **Soundness, or absence of physical defects,** such as seams, incipient cracks, internal fissures, stresses and strains. Soundness is a term generally used in connection with ingots to denote their freedom from blow holes, pipe or other sources of great weakness. The remnants, or the after-effects, of such cavities are included under this head.

III. **Crystalline, or grain, structure,** which includes the allotropic form of the iron and the size of the grains as well as any distortion produced by the action of stresses.

IV. **Uniformity:** This term includes uniform distribution of all elements and compounds, that is, freedom from abnormal segregation, and also uniformity in grain structure.

V. **Cleanness:** If a section of steel be polished and examined unetched under the microscope, a number of dark spots or pits will be seen on the surface. That these spots mark the locations of small foreign particles that have been entrapped in the steel there can be no doubt. Such particles have been called sonims or non-metallic inclusions, but the practical metallographer speaks of them merely as dirt. These particles vary in size from those scarcely visible under a magnification of 1000 diameters to filaments a hundredth of an inch in length or more. In ordinary structural steels which are used in large sections these inclusions do little harm, unless they are extremely large or very numerous, but in the fine steels, especially those used for cutting tools or for articles of very small sections that must be heat treated, they may be very injurious. Hence, in the fine steels, they should be few in number and small in size. It is practically impossible to make steel absolutely free from these inclusions.

Factors in the Preparation of the Steel Determine its Quality: With this understanding of the inherent or fundamental factors that determine the quality of steel, it is interesting to note how these may be controlled or how they are affected by the various steps in the preparation of the metal for use. To consider each and all of these steps in detail would lead to a very lengthy discussion, and to a repetition of much that has already been covered in this book. So, in order to be brief and at the same time present a complete survey of the various operations of preparing fine steels for use, with the probable general effect of each upon the quality of the steel, we have prepared the following outline.

A. **Raw Materials.** (Affects composition and chemical uniformity.)

- I. Wrought iron scrap and muck bar.
- II. Plain steel scrap.
- III. Alloy steel scrap.
- IV. Pig iron.
- V. Ferro-alloys and alloying metals.

B. **Methods of Melting and Finishing the Heats.** (Partly determines composition, and may influence soundness, chemical uniformity and cleanness.)

- I. Crucible Process.
  1. Charging the pots (only means of controlling composition).
  2. Proper "killing" of the steel.
  3. Temperature of steel at pulling and pouring.
  4. Skill and integrity of the melter.

B. Methods of Melting and Finishing the Heats.—Continued.

II. Electric Furnace Process.

1. Method of Purification.
   a. Acid.
   b. Basic.
   c. Without removal of oxidizing slag.
   d. With removal of oxidizing slag.
2. Composition of reducing slag.
3. Time under reducing slag.
4. Temperature while under reducing slag.
5. Preliminary tests and analyses.
6. Additions to control composition of the steel.
   a. Time of making additions.
   b. Composition and uniformity of additions.
7. Proper "killing" of the steel.
8. Temperature at tapping.

III. Open Hearth Process. (Though inferior to either the crucible or electric processes for making fine steels and totally unsuited for making certain kinds, some kinds of steel of high quality may be produced by this process.)

1. Composition of charge.
2. Method of purification—acid or basic.
3. Deoxidation and additions in the furnace.
4. Preliminary analyses.
5. Temperature at tapping.
6. Additions made in ladle.
   a. Chemical composition.
   b. Uniformity.
7. Deoxidation in the ladle or moulds.

C. Mill Practice. (Affects soundness, grain structure, and uniformity.)

I. Handling of Ingots.

1. Temperature of steel at time of pouring.
2. Size and shape of ingots.
3. Moulds.
   a. Open top.
   b. Closed top.
   c. Hot top.
   d. Condition of moulds.
   e. Shape and wall thickness.
   f. Big end up or big end down.

C. Mill Practice.—Continued.

4. Method of casting.
   a. Top poured—care to prevent splashing.
   b. Bottom cast.
5. Stripping and cooling.
6. Top discard.
7. Soaking.
   a. Temperature of pit and ingot.
   b. Nature of flame and pit atmosphere.
   c. Time of soaking.

II. Cogging of Ingots.

1. Rolling.
   a. Amount of draft.
   b. Care in handling bloom in rolling.
   c. Initial and finishing temperature.
   d. Amount of top of bloom discarded.
   e. Manner of cooling billets.
2. Forging—cogging with the hammer.
   a. Weight or size of hammer.
   b. Initial temperature.
   c. Manipulation of steel under the hammer.
   d. Reheating the steel—temperature and thoroughness of soaking.
   e. Inspection for and cutting out defects.
   f. Finishing temperature.
   g. Manner of cooling.
3. Forging with hydraulic press (not used extensively).

III. Handling of Billets.

1. Inspecting, chipping and grinding out defects.
2. Heating.
   a. Rate of heating.
   b. Temperature and time of soaking.
   c. Final temperature.
3. Rolling.
   a. Amount of draft.
   b. Speed of rolling.
   c. Adjustment of rolls.
   d. Design of passes.
   e. Mill inspection.
   f. Initial and finishing temperature.
   g. Manner of cooling.

C. Mill Practice.—Continued.

IV. Works Annealing.

1. Rate of heating.
2. Maximum temperature.
3. Time of soaking.
4. Uniformity of heating.
5. Protection of steel from oxidation and decarbonization.
6. Rate of cooling.

V. Final Mill Inspection.

1. Kind and number of tests for mechanical properties, including hardness.
2. Upsetting tests for seams, cracks, etc.
3. Fracture tests for structure and pipe.
4. Measurements.

D. Final Shaping. (May affect soundness, structure and uniformity.)

I. Forging.

1. Heating—manner and rate of—Maximum temperature.
2. Manipulation of steel in working.
3. Finishing temperature.
4. Inspection.

II. Machining.

1. Proper shaping.
2. Proper design of the article.

E. Heat Treatment. (Largely determines grain structure and may affect soundness.)

I. Normalizing or Annealing.

1. Rate and manner of heating.
2. Final temperature.
3. Time of soaking.
4. Rate of cooling.

II. Hardening.

1. Rate of heating.
2. Manner of heating.
3. Maximum temperature attained.
4. Uniformity of temperature.
5. Time of soaking.
6. Quenching.
   a. Medium (oil—water—brine—air—molten metals, etc.)
   b. Manner of quenching.

III. Tempering.

1. Maximum temperature attained.
2. Time held at maximum temperature.
3. Manner or rate of cooling.

From this outline it is apparent that the quality of steel is affected to a greater or less extent by each and every step in its preparation, from the selection of the raw materials to the last operation on the finished article. So far as the manufacture of the steel, itself, is concerned, its quality depends upon the raw materials available, the equipment of the plant, the manual skill of the workmen, the honesty, intelligence, knowledge, and experience of all members of the organization, and the attention and care bestowed on the steel at every step in its manufacture. This last point accounts largely for the high cost of the fine steels. As the various processes and operations indicated in this outline have been described in detail in other parts of this book, it is not necessary to discuss them further here. However, a brief description of what is considered the latest and best practice in the manufacture of the fine steels will be found under High Speed Steel, discussed in the last section of this chapter.

Classification of the Fine Steels: A satisfactory classification of the fine and extra-fine steels is difficult to make. In the beginning of this section it was pointed out that these steels may be used for many structural purposes, and for the manufacture of both hand and machine tools. This at best is but a rough classification and wholly inadequate, as is also any system of classification based on method of manufacture. Owing partly to the former policy of secrecy on the part of tool steel manufacturers, and largely now to a knowledge of the various factors that affect the quality of steel, the fine steels are not sold to chemical, physical or other specifications as other steels are, but are marketed under individual trade marks and brands, according to "grade" and "temper." The term grade refers to the quality and type of the steel,—type being a class term used to denote steels of similar composition,—and is the chief factor in fixing the price. Each manufacturer usually has a distinctive brand for each grade. The word "temper" refers to the carbon content. This custom in marketing makes the manufacturer responsible for the performance of his steel; but it is likely to continue, because it is an advantage to both the steel maker and his customers on account of the comparatively small tonnages involved in their deals. Hence, though the manufacturer must lay down for himself and observe very rigid specifications in making his steel, custom stands in the way of a comprehensive and practical system of classification based on chemical analyses, or composition of the steels, alone. Again, the diversity of elements and combinations used in making these steels also stands in the way of a chemical classification. In composition, the fine steels range from the plain carbon tool steels to the most complex alloy steels, containing four, five, and even six alloying elements. The alloying elements commonly used are manganese, vanadium, chromium, tungsten, cobalt, and silicon, but molybdenum, uranium, nickel and zirconium are also met with. For several years past heat treaters have been referring to different steels as water hardening, oil hardening and air hardening, according as the steels can be hardened by quenching in water or

oil or cooling in air. This custom suggests a classification of the fine steels based on their heat treating or other outstanding properties; but this is not a suitable basis, because the different classes would overlap. However, the fine steels fall naturally into three main groups, namely, carbon tool steels, alloy tool and special steels, and high speed steels. For convenience of discussion, we shall separate the second group into two and divide it into classes as shown in the following outline:

Table 86. Classification of the Fine Steels.

1. Carbon Tool Steels.
2. Alloy Tool Steels.
   a. Water-hardening steels.
   b. Oil-hardening non-deforming steels.
   c. Hot working steels.
   d. Finishing tool steels.
3. Special Alloy Steels.
   a. Non-corroding steels.
   b. Valve steels.
   c. Magnet steels.
   d. Non-magnetic steels.
4. High Speed Tool Steels.

SECTION II.

CARBON TOOL STEELS.

Manufacture and Grades of Carbon Tool Steel: Of the four classes of fine steels, the carbon tool steels are used for the greatest variety of purposes. They are made by the open hearth, the crucible and the electric furnace processes, but those made by the open hearth process are generally considered of a lower grade. In so far as the method of melting may affect the quality, the electric and crucible processes may be considered as being on a par, but the steels made by these processes are not to be considered as being of uniform grade, for as already pointed out, the quality also depends upon the raw materials used, the mill practice and the skill and care exercised in making the steel. Most manufacturers of electric and crucible steel will make two or more grades. After melting and casting, these steels will be cogged and rolled into bars of various weights and shapes, the standard forms being flats, rounds, squares, octagons, and hexagons. These bars may or may not be annealed by the manufacturer. As to chemical composition, the phosphorus and the sulphur in the best

grades of carbon tool steel will not be permitted to exceed .03 per cent., while the silicon and manganese may each vary from .15 to .30 per cent. The low manganese content is desirable to permit the safe quenching of the steel in water under various conditions. The carbon content varies from .60 to 1.50 per cent. according to the temper desired.

Temper: As previously indicated, temper, in tool steel parlance, refers to carbon content, and should not be confused with the heat treating process known as tempering or drawing back. Formerly, it was the custom to designate different tempers by name. Thus, die temper steel was steel with a carbon content of approximately .75 per cent.; set temper steel contained about .90 per cent.; spindle temper, about 1.10 per cent.; drill temper, about 1.25 per cent.; and razor temper, about 1.50 per cent. But as each temper can be applied to many different purposes, this custom was abandoned in favor of numbers or letters, usually the former for carbon steels and the latter for alloy steels. As methods of manufacture improved, giving closer control of the carbon content, the number of tempers increased; but as it is impossible to control the carbon exactly, each temper indicates a range in carbon content, which is now fairly well established as 10 points, or 10 hundredths of one per cent. The numbers or letters are, however, arbitrarily selected by each manufacturer, or other agency, so they have no general significance. Hence, in this book temper is indicated by giving the actual range in carbon content rather than the symbols.

Selection of Steel: Evidently the selection of the proper grade and temper of steel for the work in hand is a matter of first importance. To make this selection requires a knowledge of all the conditions of the service required and familiarity with what the different grades and tempers of steel will do under those conditions. The essential knowledge is largely a matter of experience, because, so far, no methods of measuring many of the qualities of steel have been worked out, and the usual physical tests are inadequate. For example, a .85-per cent. carbon and a 1.10-per cent. carbon steel will show about the same tensile strength, and even after quenching, practically the same Brinell and scleroscope hardness, yet the latter is capable of holding a keener cutting edge than the former. The best that can be done, then, is to indicate in a general way, by example or otherwise, some of the uses to which each grade and temper may be suited. This we attempt to do in the following table, which also indicates the proper temperatures for the forging and heat treatment of each temper.

Table 87. Showing Tempers, Uses, and Heat Treating Temperatures of Carbon Tool Steels.

Temper. % Carbon.	General Properties and Uses	Forging Range	Heat Treatment				Approxi. Brinell No.
			Anneal	Normalize	Quench	Temper	
.60 to .70	Great toughness and fair hardness. Tools for hot work, and battering tools of all kinds: Hot-forging dies, etc.	760°C. to 900°C. (1400°F. to 1650°F.)	775°C. (1425°F.) ±10°C.	830°C. (1525°F.)	788°C. (1450°F.) ±10°C.	205°C. (400°F.) 316°C. (600°F.) 427°C. (800°F.) 538°C. (1000°F.) 649°C. (1200°F.)	495 412 350 302 255
.70 to .80	Great toughness and medium hardness. Rivet sets, hammers, smith's tools, chisels, etc.	732°C. to 871°C. (1350°F. to 1600°F.)	765°C. (1410°F.) ±10°C.	815°C. (1500°F.)	774°C. (1425°F.) ±10°C.	205°C. (400°F.) 316°C. (600°F.) 427°C. (800°F.) 538°C. (1000°F.) 649°C. (1200°F.)	578 477 351 302 269
.80 to .90	Toughness, medium hardness and slight cutting edge. Pneumatic chisels, dies, hammers, scissors, shears, large springs, pliers, etc.	704°C. to 857°C. (1380°F. to 1575°F.)	760°C. (1400°F.) ±10°C.	810°C. (1490°F.)	765°C. (1410°F.) ±10°C.	205°C. (400°F.) 316°C. (600°F.) 427°C. (800°F.) 538°C. (1000°F.) 649°C. (1200°F.)	627 512 418 340 262
.90 to 1.00	Fair toughness, hardness and medium cutting edge. Knives, shears, punches, taps, reamers, etc.	732°C. to 843°C. (1350°F. to 1550°F.)	754°C. (1390°F.) ±10°C.	821°C. (1510°F.)	760°C. (1400°F.) ±10°C.	205°C. (400°F.) 316°C. (600°F.) 427°C. (800°F.) 538°C. (1000°F.) 649°C. (1200°F.)	627 495 375 286 228
1.00 to 1.10	Little toughness, Hardness and good cutting edge. Axes, reamers, milling cutters, threading dies, coil springs, etc.	732°C. to 843°C. (1350°F. to 1525°F.)	754°C. (1390°F.) ±10°C.	837°C. (1540°F.)	754°C. (1390°F.) ±10°C.	205°C. (400°F.) 316°C. (600°F.) 427°C. (800°F.) 538°C. (1000°F.) 649°C. (1200°F.)	627 495 387 286 217
1.10 to 1.20	Great hardness, with keen cutting edge. Drills, taps, lathe tools, shear knives, etc.	745°C. to 830°C. (1375°F. to 1525°F.)	754°C. (1390°F.) ±10°C.	857°C. (1575°F.)	754°C. (1390°F.)	205°C. (400°F.) 316°C. (600°F.) 427°C. (800°F.) 538°C. (1000°F.) 649°C. (1200°F.)	627 512 418 302 228
1.20 to 1.30	Very keen cutting edge and rather brittle. Balls for roller bearings, razors, glass cutters, etc.	745°C. to 843°C. (1375°F. to 1550°F.)	754°C. (1390°F.) ±10°C.	927°C. (1700°F.)	754°C. (1390°F.) ±10°C.	205°C. (400°F.) 316°C. (600°F.) 427°C. (800°F.) 538°C. (1000°F.) 649°C. (1200°F.)	627 512 430 335 241

Working and Treating the Steel: After selecting steel of the proper grade and temper, the next consideration is to put it into the form and condition to give its best service. The forming of articles from the bars supplied by the manufacturer is usually done by forging and machining, though drawing, spinning and bending are sometimes used; the conditioning by heat treatment. Lack of space will not permit a full discussion of all these operations, so only the principle features of the more common and important will be taken up under the following headings:

Forging: The chief object in forging is to shape the steel, but the fact must never be forgotten that in doing this work the steel may be injured or improved by the manner in which it is heated and worked. Heating above the critical range of the steel causes crystalline or grain growth, the amount of such growth depending upon the temperature and the time held at that temperature, while hammering, or working in any way, below the critical range distorts the grain structure and induces strains in the metal which are usually harmful and difficult to remove. If the steel is heated but slightly above the critical range and then immediately hammered or worked constantly while it is cooling to the critical range, grain growth will not only be prevented, but the structure of the steel will actually be refined and the metal improved in every way. But if the steel is heated too far above its upper critical point, no amount of hammering or working will be able to overcome the harm done by the high temperature. Hence, heating to a high temperature to decrease the number of forging operations and save time is bad practice so far as the quality of the product is concerned. It is better to fix a temperature limit, doing as much forging as possible within the forging range, and reheat as often as necessary to complete the work. This forging range varies both with the kind or grade and the temper of the steel. The forging ranges shown in the accompanying table are those which will give the best results with carbon steel, provided the steel is not heated too rapidly, is not soaked too long at the upper temperature, and is constantly worked while cooling to the lower temperature. Finally, it should be noted that the amount of deformation produced in a single operation is important. In hammering, for example, moderately heavy blows relative to the section being forged are better, from a structural standpoint, than very heavy or very light blows. If the blow is too heavy the steel may be ruptured minutely, while if the blows are too light the refining effect is produced only at the surface. The manipulation of the steel under the hammer is of great importance. The spreading of the metal when struck by the hammer tends to draw metal away from the center in opposite directions. Under certain conditions this tendency becomes so great as to actually rupture the metal, causing a central flaw equivalent to a pipe. Unless guarded against, the flow of the metal may also cause the surface defect known as hammer laps, which are as injurious as a seam produced in any other way.

Normalizing: After forging it is generally advisable in every day practice to normalize the steel in order to eliminate possibly severe forging strains, develop a uniform grain structure, and bring about an equalized distribution of all constituents of the steel, especially the cementite. These conditions are all necessary to secure the best results in hardening and to impart those structural characteristics in the steel that enable it to give maximum life and efficiency. To normalize, it is only necessary to heat the steel slowly and uniformly to the proper temperature, as indicated in the preceding table, soak for a sufficient period of time, and cool freely in air. For best results and to avoid all danger of injuring the steel, the furnace should be practically cold when the steel is charged, and the rate of heating must be regulated so that there will be no great difference in temperature between the inside and outside of the piece. Evidently, the rate of heating must be regulated to suit the thickness of the largest section, and the size of the piece—due consideration being given to the arrangement and weight of the charge and its relation to the heating capacity of the furnace. No definite directions can, therefore, be given, but an idea as to the correct relations of size of section to rate of heating may be obtained from these examples: 1-inch rounds may be heated at the rate of 20°C. (36°F.) per min.; 2-inch rounds, at the rate of 15°C. (27°F.) per min.; 3-inch rounds, at the rate of 10°C. (18°F.) per min.; 4-inch rounds, at the rate of 8°C. (15°F.) per min.; 5-inch rounds, at the rate of 6°C. (10°F.) per min.; 6-inch rounds, at the rate of 4°C. (8°F.) per min. Soaking is for the purpose not only of bringing about equalization of temperature, but also for permitting time for the adjustments necessary for the release of strains and the distribution and solution of the cementite. The time of soaking, therefore, varies with the size of the section and also the rate of heating, and may require from 30 mins. to 2 hours or more. Concerning the normalizing temperatures, it will be noticed that these are somewhat above the upper critical points, and much higher than those for annealing and hardening. These higher temperatures induce some grain growth, but are necessary for the complete elimination of severe strains. Also, it is observed that in the case of hypoeutectoid steels these temperatures decrease with the carbon content, but in the case of the hypereutectoid steels they increase with the carbon content. In the latter it is necessary to heat above the A_{ccm} points in order to break up and dissolve the excess cementite, which, if allowed to remain in massive form, imparts a brittle structure to the steel.

Annealing: If machining is to be done, the steel must be annealed, as the comparatively rapid cooling in air from the normalizing temperatures leaves the steel in a semi-hard condition. To develop the maximum machineability, especially in the hypereutectoid steels, it is a general practice to heat the steel to a point just under the critical range, about 715°C. (1320°F.), and to cool very slowly in the furnace. This treatment, referred to elsewhere as spheroidizing, causes a part of the cementite to

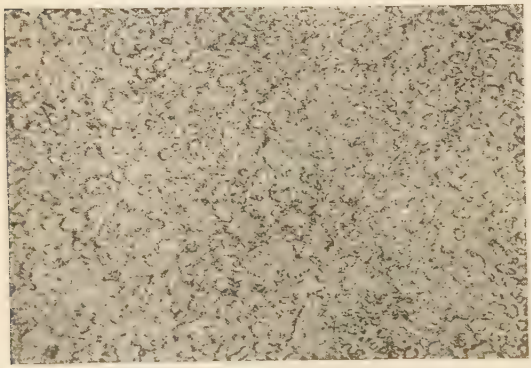
coagulate into small rounded bodies, as shown in photomicrograph No. 3, Fig. 214 on the next page. These bodies being easily pushed aside by the tool, do not dull a tool as does the lamellar structure of photomicrograph No. 1, or a net-work structure, both of which give plates of cementite that must be cut by the tool. As this treatment produces no grain refinement, the better practice, from a structural standpoint, for hypoeutectoid steels is a full anneal, in which the steel is heated slowly and uniformly to a point just over the critical range, as shown in the table, and cooled in the furnace. By this treatment the steel gets the benefit of a double refinement on hardening, and, if it is not soaked at the annealing temperature too long and the temperature is not too high, the cementite will not separate in the plate form to any great extent, as indicated by photomicrograph No. 2. If the forging has been done properly and care taken to see that the finishing temperature was not below 760° C. (1400° F.), the normalizing may be omitted, and a full anneal made to serve for both treatments. If the work is of a kind not injured by scaling, open furnace annealing is permissible, but most tools and fine-steel implements and parts must be box annealed. For this purpose it is best to pack in a mixture made up of carbonaceous and refractory materials.

Hardening: Heating, the first operation in hardening, must be done slowly and uniformly—slowly to permit the heat to penetrate the metal, and uniformly to prevent unequal expansion of different parts of the tool or other article being treated. As in normalizing, the rate of heating must be regulated in accordance with the size, form and weight of the article. In the case of articles of varying section, the thickness or diameter of the largest section of the article is made the basis for determining the rate of heating. Since it is most important to secure maximum grain refinement in hardening, the final temperature should not be permitted to rise higher than is absolutely necessary above the Ac 3-2 point for hypoeutectoid steels or above the Ac 3-2-1 point for eutectoid or hypereutectoid steels. In the the case of the hypoeutectoid steels, heating above the upper critical point is necessary to break up the pearlite and dissolve the cementite; in the case of hypereutectoid steels, heating above the Accm range to dissolve the excess cementite is not permissible, because the high temperature coarsens the grain. The temperatures shown in the table are those which experience has shown will give best results. Although long periods of soaking are not desirable, the steel should be held at the hardening temperature until all parts of the article have reached the same temperature, a condition not determinable by pyrometer but by eye only, and indicated when all parts of the piece are of the same color and free from all shadows.

Quenching, the second step in hardening, must be carried out so as to avoid warping of the article or setting up unequal stresses which may cause quenching cracks. To avoid these conditions, the cooling should be made as uniform as possible. In some cases uniformity of cooling is difficult to attain, especially in articles of irregular shape and varying cross section, but by regulating the manner of introducing the article into the quenching

Photomicrograph No. 1.
Heated above Accm.
Structure.
Wholly Lamellar.
Machineability Poor.

Photomicrograph No. 2.
Heated just over Ac3-2-1.
Structure.
Mixed, spheroidal and lamellar.
Machineability Fair.



Photomicrograph No. 3.
Heated just below Ac3-2-1.
Structure.
Wholly Spheroidal.
Machineability Good.

FIG. 214. Showing affects of annealing a 1.05-per cent. carbon steel at different temperatures. x 500. Etched with 4-per cent. nitric acid.

medium or changing the method of quenching, the cooling can often be made more nearly uniform. For example, articles containing cup-shaped depressions or cavities, as in forging dies, rivet sets, etc., uniform cooling can be obtained only by spraying. Assuming that the proper temperature was reached in heating, the hardness, fineness of grain and structural condition of the steel depends upon the rate of cooling, which can be controlled by varying the quenching medium, the temperature of the medium and the manner of quenching. For the carbon steels, water is the quenching medium almost universally used. Cold water will cool faster than hot water, while spraying an article with water cools it more rapidly than merely immersing it. The temperature of the water generally recommended is 20°C. or 70°F., and the most common method of quenching is by plunging the article into a bath of the water. To avoid the formation of steam bubbles on the surface of the steel, a saturated salt solution, brine, may be used. Since the rapid cooling lowers the transformation range to about 250°C. (482°F.) or lower, according to the rapidity of the cooling, it is possible and practicable in many cases to remove the article from the bath just before this temperature is reached and straighten it without injury before the more ductile austenite changes into the hard, brittle martensite or troostite. In any event it is always advisable to stop the quenching as soon as the article has cooled below the draw back temperature and before it has reached that of boiling water.

Tempering: Since the strains and stresses that cause cracking are mainly due to opposing forces of contraction and expansion set up by different parts of a piece undergoing transformation at different times, tempering, or drawing back, should follow the quenching immediately and while the steel is still warm. Drawing back under these conditions prevents the condition that sets up these stresses, whereas delaying the drawback until the steel has cooled to room temperature permits this condition, which may produce stresses of a magnitude sufficient to rupture the metal, when, of course, it is injured beyond repair. The temperature of the drawback offers a means of controlling with nicety the properties of the metal, and must be regulated to the work in hand and the service required. Therefore, no definite directions can be given. If hardness is required and brittleness is not a detriment, tempering to 175°C. (350°F.) will relieve stresses and prevent destructive strains. From 200°C. (392°F.) to 300°C. (572°F.) the brittleness decreases markedly and there is considerable loss of hardness, but not in proportion to loss of brittleness. Above these higher temperatures, hardness decreases more rapidly, and toughness increases up to 650°C. (1200°F.) when the steel is approaching the annealed state. Formerly, it was the universal custom to draw back by color, but as this method is affected by so many things, such as the amount and the kind of light, eye sight of the observer, the time or speed of heating, etc., it has been replaced in all the larger shops by the more exact plan of drawing back in oil baths. Concerning the time of the draw back, it is evident the article must remain in the bath long enough to become uniformly heated

to the draw back temperature. After this period is past the longer the steel remains in the tempering bath the softer it becomes, up to certain limits. This tempering by time is slow; several hours are required to produce the same result that heating to a temperature 40° to 50°C. higher would produce. As to the manner of cooling, this part of the operation is best done in air. Some articles made of lower temper steel may be cooled in water, but many articles made of higher carbon steel, especially those of light section, such as springs, may be injured thereby, because the rapid cooling sets up internal stresses which decrease the ability of the steel to resist external stress. Attempts to modify mechanical properties by quenching from the draw back temperature, as is sometimes done in the case of low carbon alloy steels, is, therefore, bad practice for the carbon tool steels.

SECTION III.

ALLOY TOOL STEELS.

Water-Hardening Alloy Tool Steels: Under this heading are included all those fine alloy steels which may be quenched in water without injury to the steel and require very rapid cooling from temperatures above their critical ranges to develop their maximum hardness. Upon slow cooling from hypercritical temperatures, they must give a pearlitic structure, and the amount of the alloying elements present are limited by this consideration. Their mechanical properties are, therefore, subject to the same variations through heat treatment as are the carbon steels. There are several types of these steels, but the four chief kinds are the simple vanadium steels, simple chromium steels, chrome-vanadium steels, and low-tungsten steels. Nickel and nickel-chrome steels, though occasionally met with, are seldom found amongst the fine steels.

Simple Vanadium Tool Steels: The vanadium steels are made to the same chemical specifications as the carbon tool steels, but with the addition of .15 to .25 per cent. of vanadium. Besides its action as a cleansing agent, vanadium tends to impart to the steel a finer grain structure than when no vanadium is added, thus producing a steel that is tougher and more resistant to shock and wear. Hence, if proper care is exercised in its manufacture and heat treatment, vanadium tool steel is superior to plain carbon tool steel. It is made in the same tempers as the carbon tool steels, is heat treated in the same way, and may be used for the same purposes. However, as it is somewhat more costly than the carbon tool steels, its use is restricted to the finer and more expensive tools, such as taps, reamers, milling cutters, etc.

Simple Chromium Tool Steels: As pointed out in the chapter on alloy steels, an outstanding characteristic of properly treated chrome steels is an exceedingly fine grain structure. Hence, chromium is used both as a hardening and as a toughening agent in fine steels. By this statement

we do not mean that a given steel will under all conditions be both hardened and toughened at the same time by the addition of chromium, though such a result may be obtained by proper heat treatment, but that by adding chromium to a given carbon steel, a steel of equal toughness but greater hardness can be obtained, or by decreasing the carbon content and adding chromium a steel of equal hardness but greater toughness can be made. Another point to remember is the fact that chromium causes steel that contains it to harden to a greater depth than carbon steel. This is a matter of considerable importance in the manufacture of many articles, especially those subjected to considerable wear. In general, the amount of chromium added varies from .2 per cent. to 2 per cent., according to the hardness desired, but amongst the fine steels there are two principal types, namely, one containing approximately .80 per cent. chromium and the other about 1.50 per cent. The first, or medium chromium, type is made in all tempers and used for various purposes requiring greater hardness and toughness or a greater depth of hardness than can be obtained with carbon steel, while the second type is used mainly for ball bearings, for which purpose about 1 per cent. carbon is required. The simple chromium steels are inferior in many respects to the chrome-vanadium steels, which have held the former to a position of minor importance amongst the fine steels. The chrome steels are more sensitive to heat treatment than the carbon steels, though their hardening ranges are wider, and occur at higher temperatures, because the chromium delays the transformation to austenite. The correct temperatures to use in treating these steels will be found under chrome-vanadium steels to be discussed next.

Chrome-Vanadium Tool Steels: It will be recalled that in the discussion of structural alloy steels it was indicated that in order to derive the greatest benefit from chromium it was necessary to add with it one of the three elements, nickel, molybdenum, or vanadium. In the case of ordinary structural steels there is some doubt as to which one of these elements makes the best combination with the chromium, but in the case of the fine tool steels opinion appears to be unanimously in favor of the chrome-vanadium over either of the other two combinations. The steel is made in several different types, but the majority of these will fall within the chemical limits shown in the following table.

Table 88. Chemical Composition of the Chief Types of Chrome-Vanadium Tool Steels.

	MEDIUM CHROMIUM	HIGH CHROMIUM
Carbon	.50 to .90% according to temper	.95 to 1.10%
Silicon	.15 to .35%	.20 to .30%
Manganese	.10 to .30%	.10 to .30%
Sulphur	.04% Maximum	.04% Maximum
Phosphorus	.04% Maximum	.04% Maximum
Chromium	.70 to .90%	1.30 to 1.60%
Vanadium	.15 to .25%	.15 to .25%

These steels are tougher than the simple chromium steels, can be made stronger and harder than simple vanadium and carbon steels, and offer, when properly treated, greater resistance to shock and fatigue or vibratory stresses than any of them. By varying the carbon and the chromium content and modifying the heat treatment, the physical properties can be nicely regulated through comparatively wide limits; so the steels are adapted to a wide range of uses. Since the chromium content, as well as the carbon, affects the temperatures at which the transformations take place on heating, both these factors must be considered in heat treating, and the temperatures varied accordingly.

The following table is intended to show some of the principal uses each type is adapted to and the proper temperatures for treating the different types. The higher carbon medium chromium and the high carbon high chromium types may be hardened in oil, in which case the hardening temperature should be raised about 50°C. (90°F.). All the precautions given in discussing the forging and heat treatment of the carbon tool steels apply also to the chrome-vanadium tool steels.

Table 89. Showing Principal Types of Chrome-Vanadium Tool Steel, Their Uses and Heat Treatment.

TYPE	PRINCIPAL USES	FORGING RANGE	HEAT TREATMENT TEMPERATURES		
			Annealing	Hardening	Tempering
.50 Carbon .80 Chromium	Machine tool parts, drop forging dies, springs, chisels, etc.	815°–955°C. 1500°–1750°F.	760°–790°C. 1400°–1450°F.	800°–830°C. 1475°–1525°F.	150°–700°C. 300°–1300°F. according to properties required by the work.
.60 Carbon .80 Chromium	Rivet sets, heading dies, gears, piston rods, auto drive and transmission shafts.	815°–955°C. 1500°–1750°F.	745°–790°C. 1375°–1450°F.	790°–830°C. 1450°–1525°F.	
.70 Carbon .80 Chromium	Punches, stone cutters, stamping tools, hatchets, forming dies.	840°–955°C. 1550°–1750°F.	745°–790°C. 1375°–1450°F.	775°–815°C. 1425°–1500°F.	
.80 Carbon .80 Chromium	Wood working tools, punches and dies of all kinds.	840°–925°C. 1550°–1700°F.	745°–790°C. 1375°–1450°F.	760°–790°C. 1400°–1458°F.	
.90 Carbon .80 Chromium	Drills, broaches, reamers, cutting tools requiring hard keen edges.	840°–925°C. 1500°–1700°F.	745°–790°C. 1375°–1450°F.	760°–775°C. 1400°–1425°F.	
1.00 Carbon 1.50 Chromium	Balls and rollers for fine bearings.	840°–980°C. 1550°–1800°F.	775°–800°C. 1425°–1475°F.	760°–775°C. 1400°–1425°F.	175°–230°C. 350°–450°F.

Simple Tungsten Steels: Though tungsten is used extensively in conjunction with other elements for making many varieties of tool and special steels, the position occupied by the simple tungsten steels is one of relatively slight importance. In amounts not exceeding 1 per cent., it is said to have been used with beneficial effects as a substitute for silicon in spring steels. Tool steels with a carbon content of about 1 per cent. and a tungsten content of 3 to 5 per cent. are said to be superior to plain carbon tool steels as lathe tools for taking finishing cuts. These steels are hardened and drawn and otherwise treated in the same way as ordinary carbon tool steels. The effects of tungsten upon the properties of iron and steel are explained in succeeding sections dealing with magnet steels and high speed steels.

The Oil-Hardening Non-Deforming Steels: The term non-deforming is used here to refer to a class of steels which show little if any change in volume from the annealed state after hardening, and tempering at low temperatures. They are frequently spoken of as non-shrinking or non-shrinkable steels and are also occasionally referred to as non-moving steels. The term non-shrinking, though sanctioned by usage, is a misnomer, because most annealed pearlitic steels will show an expansion on being hardened, and all steels change in volume in passing through their transformations. In general, and irrespective of the expansion and contraction due to the temperature changes necessary to bring about the transformations, martensite occupies a greater volume than either pearlite or austenite, so that in passing from the pearlitic to the austenitic state a pearlitic steel contracts, from the austenitic to the martensitic state it expands, and from the martensitic to the pearlitic state it contracts again. In drawing back, the contraction, in the case of most pearlitic steels, proceeds most rapidly after a temperature of 200°C. has been passed and reaches a maximum at about 600°C. so that the transition from sorbite to pearlite may be accompanied by a slight expansion. In the case of the non-deforming steels, the contraction that takes place when the steels pass from pearlite to austenite is balanced by the expansion that takes place when the austenite changes to martensite, or martensite and troostite, on quenching, and drawing back at low temperatures. Such a steel is required in the manufacture of master tools, gages, and dies that must not change size when hardened after forming, and machining in the annealed condition. There are several different types of steels that meet these conditions. The cheapest is a high carbon steel with a manganese content of about 1.50 per cent. Better grades are made by reducing the manganese content to about 1.00 per cent. and adding some combination of two or three of the elements tungsten, chromium and vanadium. They can be quenched only in oil, and the draw-back temperature should not exceed 160°C. (350°F.) to obtain maximum hardness and minimum movement, or change in volume. Representative analyses of the different types are shown in Table 90.

Table 90. Representative Chemical Specifications and Hardening Range for the More Common Types of Non-Deforming Steels.

TYPE	RANGE IN PERCENTAGE OF (1)							HARDENING RANGE
	C.	Mn.	Si.	Cr.	V.	W.	Ni.	
Carbon-Manganese	1.00/1.15	1.40/1.60	.20/.40					790°–815°C. 1450°–1500°F.
Manganese-Chromium	.95/1.10	1.00/1.20	.15/.35	.30/.50				790°–815°C. 1450°–1500°F.
Manganese-Vanadium	.90/1.05	1.30/1.50	.15/.35		.15/.25			790°–815°C. 1450°–1500°F.
Manganese-Chrome-Vanadium	.95/1.10	1.00/1.20	.15/.35	.40/.60	.15/.25			790°–815°C. 1450°–1500°F.
Manganese-Chrome-Tungsten	.95/1.10	1.00/1.20	.15/.35	.25/.35		.25/.35		790°–815°C. 1450°–1500°F.
Tungsten-Chrome-Vanadium	.95/1.10	.50/.80	.15/.35	.50/.70	.15/.25	1.80/2.20		845°–875°C. 1550°–1600°F.
High Carbon-Chrome	1.75/2.25	.20/.30	.15/.20	12.00/18.00	1.00 (?)	1.50 (?)	1.00 (?)	925°–980°C. 1700°–1800°F.

(1) Phosphorus and Sulphur each under .04%

The manganese-chromium, manganese-vanadium, chrome-vanadium and chrome-tungsten types are not so sensitive to heat treatment nor so liable to crack in quenching as the first type, hence are tougher and offer greater resistance to shock, while the tungsten-chrome-vanadium type gives, in addition, a harder and keener cutting edge. The high-carbon-high-chromium type is air-hardening and is used where resistance to oxidation is an important consideration. In order to make this steel more suitable for certain purposes, vanadium, tungsten or nickel in amounts noted in the table may be added in combination with the chromium.

Hot Working Steels: In making many articles of iron, steel, brass, and other metals, the metals must be worked hot, and the tools used necessarily become quite hot from their contact with the hot metals. For such tools, the carbon tool steels and the pearlitic alloy steels are not suitable, because the heat draws the temper and renders them too soft for the work. To overcome this defect, tool steel manufacturers have developed a class of alloy steels commonly known as hot working die steels, but since their use is not restricted to dies only, they are designated here as hot working steels. While there are many different brands of these steels on the market, there are four chief types, as shown in the accompanying table.

Table 91. Composition of Chief Types of Hot Working Steels.

TYPE	APPROXIMATE PERCENTAGE OF					
	C.	Mn.	Si.	W.	Cr.	V.
Low Carbon—Low Alloy	.50	.30	.25	2.00	1.65	.20
High Carbon—Low Alloy	1.00	.25	.30	.....	4.00	...
Low Carbon—High Alloy	.30	.20	.30	10.00	3.00	.35
High Carbon—High Alloy	2.00	.20	.20	(?)	15.00	(?)

The Low Carbon-Low Alloy type is less resistant to heat than any of the other types. It is suitable for shear blades, hot heading dies, and other tools subjected to shock or vibration. The proper temperatures for forming and treating the steel are as follows: For forging, 845°—985°C. (1550—1800°F.); for annealing, 790°—815°C. (1450—1500°F.); for hardening in oil, 840°—870°C. (1550—1600°F.); for tempering, 204°—600°C. (400°—1100°F.), according to the maximum temperature attained in working.

The High Carbon-Low Alloy Type: The chief representative of the high carbon-low alloy type of hot working steel is the chrome steel shown in the table. This steel hardens to an appreciable extent when cooled in

an air blast, and is fairly resistant to tempering. It is best suited for tools that work by compression, and has been used with great success for gripper and header dies for bolt and rivet machines and upsetting dies of various kinds. In forging this steel, the temperature should be kept between 950° and 1000°C. (1750° and 1825°F.). The annealing range is between 815° and 845°C. (1500° and 1550°F.), while the hardening range may be said to lie between 845° and 980°C. (1550° and 1800°F.). The best results in hardening are obtained by heating the steel slowly and uniformly to 950°C. (approximately 1750°F.) then cooling in a good air blast to atmospheric temperatures and drawing at once to a temperature between 370° and 620°C. (700° and 1150°F.) according to the hardness desired. Gripper and header dies, for example, are drawn at 590°—600°C. (approximately 1100°F.).

The Low Carbon-High Alloy type, with the combination of elements given in the example, represents the best grade of steel for all kinds of hot work, except where resistance to scaling, or oxidation, is a property of importance. It is used for header, swedging, hot forming, hot drawing and hot forging dies, also for shear blades, piercers, punches, flying shears, etc., and, when the carbon is increased to about .55 per cent., it is especially adapted to extrusion dies. It is readily forged, and easily machined when properly annealed. The forging range is between 875° and 1065°C. (1600° and 1950°F.) and the annealing range is 855° to 870°C. (1575°—1600°F.). In heat treating, the steel is handled like a high speed steel, being preheated slowly to about 815°C. (1500°F.) before transferring to the hardening furnace, which is held at the hardening temperature. The hardening temperature varies from 1040°C. (1900°F.) to 1200°C. (2200°F.) according to the kind of work the tool has to perform. The steel is air-hardening, hence may be cooled in an air blast or quenched in oil. If quenched in oil, the tool is heated to the higher temperature, and drawn, while still hot, from 600°C. to 730°C. (1100° to 1350°F.).

The High Carbon-High Alloy Type has a carbon content that varies from 1.75 to 2.50 per cent. and a chromium content that ranges from 13.00 to 18.00 per cent. in different brands. Occasionally tungsten and vanadium, also, are added to increase the strength of the steel at high temperatures. It is used instead of the preceding types particularly when great resistance to oxidation at high temperatures, combined with great hardness, is required. It has good wearing qualities, and is also frequently used for cold work as well as hot work. It gives excellent service on such tools as forming dies and both hot and cold punches, and excels all other steels for roller threading dies. The steel is rather difficult to forge, for which purpose a temperature of about 980°C. (1800°F.) is required. It gives a martensitic structure on cooling in air, but the chromium carbides can be thrown out of solution and the steel annealed by cooling very slowly from a temperature of about 840°C. (1550°F.). It is hardened by heating to

about 980°C. (1800°F.) and cooling in air, or to 870°C. (1600°F.) and quenching in oil. The quenched steel may be drawn to 480°C. (900°F.) without material loss in hardness.

Finishing-Tool Steels: While the high speed steels described in the last section of this chapter exhibit the astonishing property of holding a cutting edge that is very efficient with heavy cuts and high speed, they are incapable, especially at the necessarily slower speeds and lighter cuts, of holding the keen razor-like edge required to give the unusually smooth finish desired on the machined surfaces of certain articles made of steel and of other metals. To obtain such a smooth surface or to secure accuracy after rough machining with high speed steel or stellite, therefore, a light finishing cut must be taken with a tool made of another kind of steel. High carbon tool steel can be used for this purpose, but the speed is very slow and the tool requires frequent grinding and touching up to maintain the cutting edge, especially in machining high carbon, heat treated, or alloy steels. In an attempt to produce a steel with the endurance of high speed steel and the keen-cutting qualities of high carbon steel, tool steel manufacturers have developed types of alloy tool steel commonly spoken of as finishing steels. While these steels lack the endurance of high speed steels and cannot be run at high speeds nor used for heavy cuts, they are capable of retaining a keen cutting edge for much longer periods than carbon tool steels under the same conditions of service. There are many different brands of these steels on the market, and formerly they were of several different types, but they are now rapidly approaching a standard in composition. The best type contains approximately 1.25 per cent. of carbon, 5.00 per cent. of tungsten, 1.50 per cent. of chromium and .50 per cent. of vanadium, with the manganese, silicon, sulphur and phosphorus contents about the same as in the carbon steels. In forging and heat treating, this steel is handled in about the same manner as ordinary carbon tool steel. The temperature range for annealing and hardening is 785°—800°C. (1450° to 1475°F.). The steel may be quenched in water, in which case it should be tempered while still hot to about 230°C. (450°F.), but for an especially keen edge it is quenched in oil without drawing. After hardening, the cutting edge is formed by grinding, first with a medium hard, fine-grained stone and finally with an oil stone.

SECTION IV.

SPECIAL ALLOY STEELS.

Definitions: Under the heading of special alloy steels are included all those steels that have some useful physical or chemical property developed to a high degree, or that possess properties that make them particularly suited to a certain purpose or certain purposes. As shown in the outline giving our classification of the fine steels, these steels fall into four main classes, which we have designated as non-corroding steels, valve steels,

magnet steels and non-magnetic steels. Lack of space does not permit a full discussion of all these classes, but an attempt is made in the following paragraphs to give some of the most interesting facts in connection with each class.

Non-Corroding Steels are those that do not rust in air and resist the action of acids or other chemicals to a marked degree, also the scaling action of air at high temperatures. Besides the nickel steels already described, several other steels with rust-resisting and non-corrosive properties had been developed up to 1924. These are sold under various trade names and are practically all protected by patents or patents pending. As to chemical composition, these steels vary from complex alloys containing nickel, chromium, and silicon, in addition to the usual elements found in carbon steel, to simple chromium steels. Of the latter there are two principal types, namely, one containing from 25 to 30 per cent. chromium and the other about 14 per cent. Of these, the latter type, sold under the trade name of stainless steel, is the best known, and at present the most widely used. It is generally made to chemical specifications that fall within the following limits:

Carbon	.25—.40 per cent.
Manganese	.20—.45 per cent.
Silicon	.20—.30 per cent.
Sulphur	.03 max. per cent.
Phosphorus	.03 max. per cent.
Chromium	12.00—15.00 per cent.

Non-Corroding Properties of Stainless Steel: When properly heat treated and polished, this steel resists corrosion by air, water, fruit juices, decayed organic matter, hydrogen sulphide, and nitric acid, and does not tarnish when heated in air, until the temperature exceeds some 450°C. (810°F.). It begins to scale at about 815°C. (1500°F.), and does not resist attack by hydrochloric acid. It can be dissolved with sulphuric acid, and is readily etched with mixtures composed of hydrochloric acid and nitric acid, hydrochloric acid and copper sulphate, or hydrochloric acid and ferric chloride. The steel becomes less resistant to corrosion and staining as the chromium content is decreased below 13 per cent. or the carbon content is increased above .40 per cent. No advantage, so far as stainless properties are concerned, are to be obtained by increasing the chromium content above 15 per cent. The steel exhibits its stainless properties best when in the hardened state and highly polished. While it is highly resistant to corrosion in the annealed state, its stainless properties are noticeably less than in the hardened state. A rough machined surface exposed to the air will generally corrode to a noticeable extent in a short time. If the metal is kept in contact with another metal that does corrode, like brass, electrolytic action will cause the steel to corrode, also. Scale has a similar effect, but natural rust deposited on the steel has no effect. From these statements, it follows that the steel cannot be advantageously case hard-

ened, nor satisfactorily plated with any of the common metals. It can readily be electrically welded, so parts to be plated can be made of carbon steel and joined in this way.

Heat Treating and Physical Properties: A reference to the constitutional diagram for chromium steels given in the chapter on structural alloy steels shows this steel to be martensitic. Hence it hardens in air on cooling from above the critical range, and cannot be normalized. On heating slowly the critical point occurs at about 810°C. (1490°F.), and on cooling slowly it occurs at about 740°C. (1365°F.). On account of the retarding effect of the chromium upon the transformation, the hardening temperature must be considerably above the higher of these two temperatures. For hardening purposes, a comparatively wide temperature range may be used with satisfactory results. The steel appears to give its maximum hardness when quenched in oil from 1065°C. (1950°F.), while quenching from 950°C. (1742°F.) gives less hardness but greater ductility. Tempering at temperatures below 400°C. (750°F.) has little if any effect upon the hardness, and between 425°C. and 550°C. (800° to 1000°F.) the mechanical properties change so rapidly that it is difficult to control them. In the hardened state, the structure is uniform and similar to that of other hardened steels, but after annealing, the structure consists of double iron-chromium carbide grains in a matrix of iron-chromium alloy, which corresponds structurally to the free ferrite of low carbon steels. Annealing for several hours at 750°C. (1382°F.) spheroidizes these carbides, so that the steel becomes softer and more ductile, and can be easily machined or cold drawn. The mechanical properties corresponding to these various treatments are shown in the accompanying table. The coefficient of expansion of the steel is low, being .00001091512, while the thermal and the electrical conductivity is about 25 per cent. of that of carbon steel. The steel can be highly magnetized, and makes a good permanent magnet. In this respect it differs markedly from other non-corroding steels containing nickel, which are non-magnetic.

Table 92. Mechanical Properties of Stainless Steel After Various Heat Treatments.

HEAT TREATMENT			MECHANICAL PROPERTIES				
Annealed	Quench (in Oil)	Draw	T. S. lbs./sq. in.	E. L. lbs./sq. in.	Elongation in 2 in.	Reduction of Area	Brinell No.
750°C. (1380°F.)			90,000 to 105,000	50,000 to 70,000	20% to 25%	55% to 65%	190 to 225
	950°C. (1750°F.)	427°C. (800°F.)	220,000	140,000	4%	12%	512
	1120°C. (2150°F.)	650°C. (1200°F.)	155,000	127,000	11%	45%	321

The Uses of Non-Corroding Steels are practically unlimited, and in England stainless steel is used extensively. In this country its use heretofore has been restricted to cutlery, surgical and dental instruments, etc., but the use of these steels is rapidly being extended to other fields, such as automobile and airplane engine valves, pump rods and valves, fittings that come in contact with sea water or mine water, also hot dies and extrusion dies. So far as stainless steel is concerned, the treatment should be varied to suit it to different purposes. Examples may be cited as follows:

For Cutlery—Harden in oil from 950°C. (1742°F.) and temper at 285° to 425°C. (550° to 800°F.).
For Dies —Harden in air from 950°C. (1742°F.).
For Punches—Harden in air from 950°C. (1742°F.) and temper at 200 to 300°C. (392°F. to 572°F.).
For plungers, pump rods, rifle barrels, turbine blades, valves, etc.,—Harden in oil from 950°C. (1752°F.) and temper at 600° to 650°C. (1112°F. to 1202°F.).

Valve Steels are steels especially designed for use as valves in internal combustion engines, particularly automobile and airplane engines. The characteristics most desired in these steels are strength, resistance to wear, resistance to oxidation at temperatures corresponding to a red heat, and ability to hold their shape through a very great number of changes in temperature. Various compositions have been tried for this purpose, ranging from cast iron to complex alloy steels. Valves with cast iron heads welded to steel stems are still used on low-priced cars. These valve heads resist scaling sufficiently well for the purpose, but are unsatisfactory on account of their tendency to warp and pit badly. Among the cheaper steels 3.50-per cent. nickel and low chromium-low tungsten steels have been used, but neither resist scaling and wear very well. Among the finer steels, the use of stainless steel has already been mentioned, and, in addition, four different types especially designed for the purpose have been used. The approximate composition of each of these four types is shown in the accompanying table.

Table 93. Composition of Fine Valve Steels.

TYPE	APPROXIMATE PERCENTAGE OF (1)						
	C.	Mn.	Si.	Ni.	Cr.	W.	Co.
Chrome-Tungsten	.65	.20	.10	....	3.50	14.00	....
Chrome-Nickel	.40	.40	.10	2.50	13.00	.....	....
Chrome-Silicon	.45	.30	4.00	....	10.00	.....	....
Chrome-Cobalt	1.30	.25	.50	.50	13.00	.....	3.25

(1) Phosphorus and Sulphur each under .04 per cent.

Of these steels, the chrome-cobalt type is said to be the best. The chrome-tungsten, by virtue of its high tungsten content, retains its strength at high temperatures but does not resist scaling as well as the other types which have a high chromium content. While the chrome-nickel and chrome-silicon steels do not scale, they do not hold their shape in service quite so well as the chrome-tungsten steels. In the chrome-cobalt type, the high chromium content imparts great resistance to scaling, while the cobalt appears to give the strength needed to resist warping. In preparing these steels for service, the high chromium types are treated in about the same manner as stainless steel, and the chrome-tungsten type like a high speed steel.

Magnet Steels are used for making so-called permanent magnets, which are widely applied to hand uses, and also in the manufacture of small dynamos and electric motors. The most important properties of such magnets is their retentivity, or ability to retain magnetism, and their coercive force. Retentivity is measured by the amount of magnetism (flux density, or lines of force per sq. cm. or sq. in.) that remains in the steel after removal of the magnetizing force, and is called remanence. The coercive force indicates the tenacity with which a magnet retains its magnetism. Retentivity depends on the form of the magnet and the steel it is made of. Thus, a steel in the form of irregular bodies, short rods, cubes and balls does not retain its magnetism nearly so well as when it is in the form of long bars, and if the bars are bent so as to form a closed or nearly closed magnetic circuit, such as in the common horse shoe magnet, the steel retains its magnetism even better. The retentivity of the steel itself depends on its chemical composition, its grain form, and the way it is heat treated.

Retentivity and Chemical Composition: As is well known, pure iron will not retain magnetism at all, and low carbon steels retain less than high carbon steels. Other elements that increase the hardness of the metal have an effect similar to carbon. The most important of these are chromium, tungsten and cobalt. The chrome magnet steels, generally, contain from .80 to 1.00 per cent. carbon and from 3.00 to 4.00 per cent. chromium, with silicon and manganese each under .25 per cent. and sulphur and phosphorus under .03 per cent. Tungsten magnet steel contains about .70 per cent. of carbon and about 6.00 per cent. of tungsten. This steel has greater retentivity than the chrome steels, and will maintain, if properly treated and handled, an almost constant magnetization for indefinite periods of time. Up to 1920, this steel was the best made for this purpose, but it is now excelled by the alloy discovered by K. Honda and S. Saito and known as K. S. magnet steel. This steel, if it may be designated as such, contains carbon .40 to .80 per cent., chromium 1.50 to 3.00 per cent., tungsten 5.00 to 9.00 per cent., and cobalt 30.00 to 40.00 per cent. The coercive force for this steel is said to be three to four times that of the best tungsten steel, which is about 60, and its residual magnetism is also greater. As

this alloy is expensive, it is not likely to replace the chrome and tungsten steels to any great extent.

Grain Form and Heat Treatment of Magnet Steel: In order for a chrome or tungsten steel magnet to retain the maximum amount of magnetism, it is necessary that the steel be made as hard as possible and hardened in the same condition as when it comes from the rolls. Hence it is important that the magnet be formed and hardened without annealing, if possible. If the steel is too hard for the machining or drilling required, it may be softened somewhat without changing the grain structure materially by heating to a point just under the critical range (about 700°C.) and at once cooling moderately slowly, as in lime. After the magnet has been shaped, it is heated to a point just above the critical range, about 800°C. (1475°F.), and quenched in water. It is then drawn in steam for several hours, or at a temperature of 120° to 150°C. (250° to 300°F.) in the usual manner, after which treatment it is magnetized as strongly as possible, usually with an electromagnet, then seasoned, or aged. Aging is accomplished by immersing the magnet, for periods of about an hour, alternately in boiling water and in ice water, and repeating this process some 5 to 10 times. This aging causes the steel to lose a little of its magnetism, but that which remains is practically constant and permanent unless the magnet is roughly handled or heated to a higher temperature. K. S. magnet steel is said to require no aging and is hardened by quenching in heavy oil from about 950°C. (1750°F.).

SECTION V.

HIGH SPEED STEELS.

Forerunners of High Speed Steel: Modern high speed steels are the result of more than half a century of experimentation with alloy steels for cutting purposes. Their history begins with the discovery of air-or self-hardening steels about 1868. This property of hardening in air possessed by many of the alloy steels of today was discovered by Robert Mushet, who was the first Englishman to make tungsten steel. The first attempt to use tungsten in steel was made by an Austrian named Jacob in 1855. Mushet was studying the effects of manganese, tungsten and other elements on iron with the object of improving ordinary carbon steel, when, in the course of some experimental work, he observed that one of his bars that contained rather higher percentages of tungsten and manganese than usual became very hard after heating and cooling in air, without the usual quenching. Further investigation showed that this steel not only did actually harden in air, but was apparently harder than even ordinary tool steel which had been quenched in water. Believing that this remarkable property of the new steel could be turned to good advantage in the production

of tool steels, Mushet immediately set out to develop tungsten steel for this purpose, and after experimenting with hundreds of different mixtures melted in crucibles, he was able to produce a tool steel, which, in addition to being air-or self-hardening, was superior to any other steel then in use. This steel was marketed under the name of "R. Mushet's Special Steel," and for many years the methods of its manufacture were kept secret. The steel is said to have contained from 1.50 to 2.00 per cent. of carbon, from 1.00 to 2.50 per cent. of manganese, from .75 to 1.25 per cent. of silicon, from 7 to 12 per cent. of tungsten, and, occasionally, from .10 to .50 per cent. of chromium. This wide variation in the composition was due to the fact that metallurgy in those days was in a more or less empirical state, and the alloys used varied widely in composition.

Heat Treatment of Mushet's Steel: The variable composition of Mushet's steel made it difficult to forge. All varieties would crack if heated above a full red heat (about 750°C.) and would sometimes crumble if heated to a higher temperature. On the other hand, the steel would sometimes crack when hammered or bent at a cherry heat (700°C.), while at other times it could be forged until almost black. To harden the steel after forging, it was at first the practice to heat the steel to a red heat and cool in air, but, after the steel had come into general use, it was accidentally discovered by users that better results were obtained if the tool, especially the tip or cutting edge, was cooled in an air blast. Thus encouraged to experiment, many of those handling the tools later found that it was still further improved by hardening at a higher temperature, i. e., an orange or yellow heat.

Other Air-Hardening Steels: Mushet never reaped the full rewards to which he was entitled through his wonderful discovery. The only work in which his tools showed to advantage was in turning and planing hard steel and cast iron. They permitted this work to be done at much greater speed, and made it possible to machine metals much too hard for any other tools. But since the machines then in use were adjusted in both speed and power to the older carbon steel tools, they could not be used to speed up work, and were bought by the machine shops only to save grinding or to do work too hard for the ordinary tools. Not until after Taylor and White's famous investigations (see p. 794) were made known in 1900, did machines adapted to take full advantage of the cutting properties of this steel begin to appear. Before this time, however, the steel manufacturers had put on the market various substitutes for Mushet's steel. In England these substitutes were known as self-hardening steels, while in the United States they were designated as air-hardening. During that period, knowledge gained concerning the steels, aside from the beneficial effects of high hardening temperatures, which were known only to a few, was confined mainly to their composition. It was found that the self-hardening properties depended chiefly upon proper combinations of carbon, tungsten and

manganese, or carbon, tungsten and chromium, also that molybdenum could be substituted in whole or in part for the tungsten. In 1900 the air-hardening steels marketed in the United States were of about four different types, each of which had, with respect to the alloying elements added, approximately the composition shown below:

Carbon, Per Cent.	Manganese, Per Cent.	Chromium, Per Cent.	Tungsten, Per Cent.	Molybdenum, Per Cent.
1.60	.50	3.70	7.60	....
2.20	1.35	.60	6.00	....
1.20	.40	2.00	8.00	....
1.40	1.50	3.50	....	4.50

Effects of Tungsten in Steel: The preceding descriptions imply that the self-hardening property is imparted not by tungsten alone but by tungsten in combination with manganese or chromium and carbon. Indeed, tungsten alone, unlike nickel, chromium or manganese, is incapable of producing any marked self-hardening properties. The effects of tungsten alone upon the physical properties of steel were exhaustively investigated by Hadfield in 1902-3[1]. He showed conclusively that tungsten alone or in the presence of less than .80 per cent. carbon does not materially affect the tensile strength, the elastic limit, the elongation or the reduction of area of annealed or forged specimens, even when the tungsten content has been increased to as high as 16 per cent.; that a .15 per cent. carbon steel containing as little as .20 per cent. of tungsten could not be hand welded; that tungsten added to ordinary high carbon steels greatly increases its magnetic retentivity, but that tungsten per se, that is, without carbon, did not confer any special magnetic properties; and that the effect of tungsten upon the electrical conductivity is less than that of any other alloying element. In all, except with regard to welding, the effects of tungsten differ widely from those of manganese, chromium and nickel. The influence of tungsten is most noticeable in its effects upon the critical points. Thus, on the steel used in Hadfield's investigation, Osmond found that, when steels containing 1.50 per cent. or more of tungsten were cooled slowly from 850°C., the critical points did not sensibly differ from those of ordinary steel with similar percentages of carbon. If, however, the steels were heated to about 1040°C., the Ar_1 point was sharply lowered, while the Ar_3 and Ar_2 points remained unchanged; and if the steels were heated to about 1300°C., all Ar points were lowered and the Ar_3 and Ar_2 points tended to join with the Ar_1 point. Osmond also noted that under certain conditions the Ar_1 point appeared to be divided, that is, it would occur in two steps. Other investigators have asserted that the Ac points, the critical temper-

[1]See Alloys of Iron and Tungsten, by R. A. Hadfield. Journal of the Iron and Steel Institute (British) Volume 11, 1903.

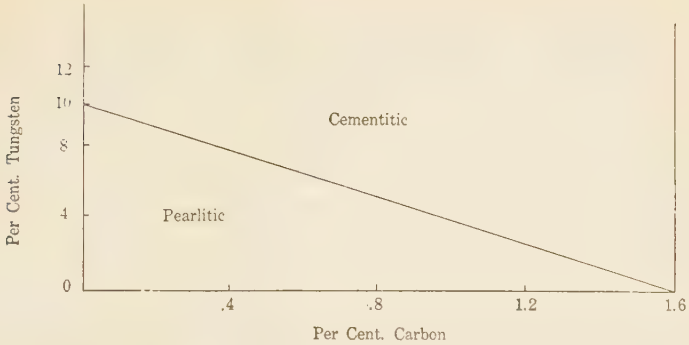


FIG. 215. Constitutional Diagram for the Simple Tungsten Steels (after Guillet).

atures on heating, are raised by tungsten rather than lowered. According to Guillet, the simple tungsten steels are either pearlitic or cementitic, on slow cooling, depending upon the content of carbon and tungsten, as shown on the accompanying diagram. Chemically, tungsten is capable of combining with carbon to form the carbide, WC, and with iron to form a tungstide, Fe_2W. Both of these compounds are probably capable of forming eutectics, or eutectoids, with iron, and dissolve with difficulty in austenite, requiring a higher temperature than that for the solution of the iron carbide, or cementite. On cooling slowly, the tungsten-bearing compounds are precipitated at much lower temperatures than that at which ordinary pearlite forms. These statements explain the peculiarities of the Ar. point for tungsten steels observed by Osmond.

Self-Hardening Explained: To be self-hardening a steel must be capable of retaining a martensitic structure without quenching. Since tungsten gives only a pearlitic or a cementitic structure on cooling in air, the self-hardening property of the steels described in this section cannot be due alone to their tungsten content, but to their chromium or their manganese content, both of which elements separately or together are capable of imparting to steel the ability to retain the martensitic structure. In other words, these elements, by their obstructing influence, make martensite a more stable phase in the transformation than it is in ordinary pearlitic steels. Tungsten, however, plays an important part in the steels in question. The martensite stabilized by chromium and manganese is very brittle; tungsten, probably by reacting with carbides of these elements and iron, tends to and does toughen the metal to such an extent that the hardness can be utilized in metal-cutting tools. More details concerning the combined effects of tungsten and chromium will be brought out in connection with the following study of high speed steels.

Development of Heat Treatment for High Speed Steels: At the Paris Exposition in 1900, the Bethlehem Steel Company exhibited some tools, the performance of which created the greatest astonishment. Prior to this time, a cutting speed of 30 feet per minute was considered a good average for tools made of ordinary carbon tool steel, and 50 feet per minute was very unusual. With speeds much higher than these, the heat generated by the friction of cutting is so great that, no matter how carefully the carbon steel tool had been hardened, the temper would be drawn in a very short time, when the tool would lose its cutting edge or break down completely. But here were tools that could be run for hours at speeds of 100 to 150 feet per minute, and would continue to cut for some time even when the speed was increased to the point where the tip of the tool became a dull red in color. At the time, the information was given out that the steel had been developed by Fred W. Taylor and Maunsel White, both employees of the company, and for some two years or more the steel was known as Taylor and White Steel. Later, full details of their discoveries were published.[1] Briefly, the circumstances connected with their initial discovery were about as follows: In 1898 the Bethlehem Steel Company engaged Mr. Taylor as an efficiency engineer to take charge of their machine shop and, if possible, increase its output, and in order to prosecute the work of improving conditions he at once associated with himself Mr. White and other members of the organization. As part of their program for increasing the efficiency of the shop, they began a study of the various self-hardening steels then on the market, to determine which steel, if any, was best, or what steel was best for each particular purpose. After a great number of tests, they selected steel of a certain make that their tests had indicated could be run at a higher speed than any of the others. To demonstrate the superiority of this steel to their foreman, they decided to call them to witness a comparative test. Accordingly, tools of the same size, shape and treatment were ordered made from the different kinds and brands of steel. When the test was executed, however, the steel they had selected as the best showed up, much to their chagrin, the poorest of all in performance. They concluded that the steel had not been properly heat-treated for the test. This idea led them to undertake another series of investigations to determine if different steels required different treatment and just what the best hardening temperature for each steel should be. Of course, this meant they must work over a rather wide range of temperatures, in spite of the fact that the hardening range had hitherto been generally considered to be very narrow both for the carbon and the air-hardening steels, and about the same for both. While carrying out some of their many experiments, these investigators made what was to most people at that time a surprising discovery—as startling, perhaps, as Mushet's discovery of air-hardening steels, itself, and of even greater economic importance. It was that the air-hardening tungsten-bearing steels, contrary

[1] F. W. Taylor, "On the Art of Cutting Metals," Trans. American Society of Mechanical Engineers. Vol. XXVIII, Presidential Address, 1906.

to the common belief that all steel was injured or ruined by hardening above red heats, were actually improved by higher quenching temperatures. Indeed, the quenching temperature had to be considerably above the usual temperature for carbon steels before any great improvement was noticeable, and if the steel was quenched or air-cooled from a temperature near its melting point, the tool held a cutting edge with heavier cuts and at higher speeds than had ever before been thought possible.

Composition and Treatment of Taylor and White Steel: After making this discovery, Taylor and White next turned their attention to a study of the composition of the steel and the development of a method of heat treatment that would give the best results. This work occupied years of time and cost more than $150,000, but in the end they were able, with practically the same force of men and number of machines, to increase the output of their company's machine shop by more than 500 per cent., so that the increase of efficiency was nothing less than astonishing. The steel they at first decided to adopt had approximately the following composition: carbon, 1.85%; manganese, .30%; silicon, .15%; tungsten, 8.00%; chromium, 3.8%; phosphorus and sulphur, under .04%. Later, Taylor recommended a carbon content of .65 to .70 per cent., a tungsten content of 17.00 to 18.00 per cent., and a chromium content of 5.50 to 6.00 per cent., with other elements as given in the previous analysis. As to the heat treatment, Taylor and White at first recommended a somewhat complicated method of heating and cooling, on which they secured patents in 1901, but others soon discovered a much simpler treatment would suffice. Later Taylor and White, themselves, after investigating this matter most thoroughly and exhaustively, reported that the essential features were a high hardening temperature followed by a relatively high draw-back temperature, and that, provided the steel was not heated or cooled too rapidly or too slowly, the manner of heating and of cooling was immaterial. Taylor and White were unable to obtain patents on any of the steels they developed in their experiments.

Elements Used in Early High Speed Steels: Taylor and White's first announcement was followed by feverish activity on the part of the manufacturers of tool steels, and there soon appeared on the market hundreds of brands of tool steel as substitutes for the Taylor and White steel. In Europe these steels were known as quick-cutting or rapid steels, but in the United States they were called high-speed steels. During the period from 1900 to 1915 the attention of manufacturers in this country was divided between composition and heat treatment on the one hand and methods of manufacture on the other. Concerning the latter, the only outstanding change was the adoption of the electric furnace as a substitute for the crucible process, while work along heat-treating lines failed to produce anything of economic importance. As to composition, practically every element at all suitable, or likely to prove suitable for the purpose, as well as almost every conceivable combination of these elements, has been tried

out, and, although from time to time announcements have been made of some supposedly startling discoveries, time and trials have shown that these new, or so-called new, steels could not meet expectations, and that most of them were inferior to the carbon-tungsten-chromium combination recommended by Taylor. Of the many elements experimented with, molybdenum and uranium have probably attracted the most attention, but the only ones that have proved of real benefit in high speed steel are vanadium and cobalt. Vanadium, in particular, has been found so beneficial that it is now added to all American-made high speed steel. Briefly summed up, the effects of these elements are as follows:

Molybdenum, as pointed out previously (see Chap. IV, Sect. VII), may be added to high speed steel as a substitute for part or all of the tungsten. Its effects in imparting high speed properties to steel are about the same as those of tungsten, and since its atomic weight (96) is little more than half that of tungsten (184), only half as much need be used to produce the same effect. As stated in the section on molybdenum steel, it has one peculiar chemical property, however, that has caused its use as a substitute for all or any large portion of the tungsten to be abandoned. When a steel containing a high percentage of molybdenum is heated to a forging temperature it gives off a yellowish fume, which, from chemical tests, appears to be a volatile oxide of molybdenum. In a molybdenum high speed steel, this action may extend to a considerable depth beneath the surface of the steel, and makes it difficult to forge and heat treat a molybdenum steel tool without demolybdenizing it to such an extent that its high speed properties are seriously affected. When used as a substitute for only a part of the tungsten, provided the proportion added does not much exceed 2 per cent., it gives good results and has been so used in many brands of high speed steel, especially those of foreign make.

Uranium oxidizes readily, and, in melting the heats, it is difficult to prevent the formation of some uranium oxides. These oxides remain suspended in the steel and have the same effect as dirt, or sonims, in steel, weakening its structure and making it liable to crack in heat treating and to break in service. This property outweighs any good effects the element may have upon the steel and makes it a detriment rather than a benefit when added to high speed steel.

Vanadium was first used in high speed steel about 1902, and for the next 10 years or more there was much difference of opinion as to whether it was of any real benefit. However, its status is now well established, and in this country it is considered a necessity in all first quality high speed steels. Aside from its effects as a scavenger, or cleanser, of the steel, it is said to have a hardening effect, while at the same time it increases the toughness of the steel. This effect shows up as an improvement

in the cutting qualities at high speeds and as an increase in the length of time the tool can be used without regrinding. The proportion of vanadium required to develop these qualities to a worth-while extent is between 1 and 2.00 per cent.

Cobalt, as an addition to high speed steel, first came into prominence about 1911, and has since proved itself of considerable worth in high speed steel for heavy duty purposes. This result was in the nature of a surprise, for cobalt belongs chemically to the same group of elements as nickel, which had not been found beneficial. But cobalt, under certain conditions of service, increases the ability of the steel to hold its edge, especially at a red-heat. High speed steels containing cobalt have been used in a few instances to machine manganese steel, which is considered unmachineable, and for machining cast iron or hard steel articles, there are many instances where they have been said to give twice the service of ordinary high speed steel.

Composition of Modern High Speed Steels: The scarcity of tungsten and the disturbed condition of commerce during the World War caused great diversity in the composition of high speed steels, but since that period the former experiences of the manufacturers in this country are causing them all to adopt chemical specifications that are almost identical. This statement is not intended to mean that all high speed steel has or can have the same composition, for different uses to which it is applied require differences in properties or costs that can be brought about only by variation in the composition. What it means is, that the composition the steel should have for best performing any certain kind of work has been fairly well worked out and is rather generally known, so that different brands intended for the same kind of work will all be of practically the same composition. Thus, while the composition of brands designed to do the same work will vary slightly according to the ideas of individual manufacturers, a careful survey of the whole field, and analyses of many different brands, indicate that the high speed steels manufactured in this country fall into two main divisions of four and five types, respectively, when classified according to chemical composition. These types, and the approximate composition of each, are given in the following table.

Table 94. Chemical Compositions of Modern High Speed Steels Manufactured in the United States.

	TYPE	COMPOSITION, RANGE IN PER CENT. OF[1]						
		C.	Cr.	W.	V.	Co.	Mo.	U.
ORDINARY TYPES	Low Tungsten–High Vanadium	.65/.75	3.25/4.25	13.00/14.50	1.50/2.00			
	High Tungsten–Low Vanadium	.65/.75	3.50/4.50	17.50/18.50	.90/1.25			
	Low Tungsten–Cobalt	.65/.75	3.25/4.25	13.00/14.50	1.40/2.00	2.50/4.00		
	High Tungsten–Cobalt	.65/.75	3.50/4.50	17.00/18.00	.90/1.25	3.00/4.00		
SPECIAL TYPES	Low Tungsten–Low Vanadium	.65/.75	3.00/4.00	12.00/13.50	.90/1.20			
	Special Low Tungsten–Low Vanadium	.60/.70	3.00/4.00	12.00/13.00	.30/.50			
	Tungsten–Molybdenum	.60/.70	3.00/4.00	12.00/13.00	1.50/2.00		.60/.90	
	Cobalt–Molybdenum	.65/.75	3.50/4.50	17.50/18.50	.90/1.25	4.00/5.00	.90/1.20	
	Tungsten–Uranium	.60/.70	3.75/4.25	16.50/17.50	1.00/1.25			.20/.30

[1] In practically all high speed steels the manganese content is under .30 per cent., phosphorus and sulphur are each under .04 per cent., and silicon ranges from .20 to .40 per cent.

Purpose of the Different Types: From the preceding table it will be observed that high speed steels manufactured in this country are virtually tungsten-chromium-vanadium steels, to which may be added, on occasion, the other special elements cobalt, molybdenum or uranium, singly or in combinations. As to the relative merits of these different types, there is little to be said except that each may excel in certain kinds of work and none of them can be considered a general purpose steel equally suited to all kinds of work. All are good cutting-steels, but not all are suitable for finishing. Of the special types, the low tungsten-low vanadium type is used for taps and similar tools, while the special low tungsten-low vanadium type is designed particularly for reamers. As to the ordinary types, the high tungsten-low vanadium type is the one most generally used. In 1923, probably 85 per cent. of all the high speed steel made in this country was of this type. As already pointed out, the steels containing cobalt are conceded to be superior for heavy duty roughing tools, but beyond this no general statement can be made as to the relative merits of any of these ordinary types. Lacking reliable methods of testing, the buyer has no way of intelligently judging the quality of a high speed steel except by trial in actual service. Various quick lathe tests have been devised and tried, but these have generally proved unreliable for predicting even the cutting qualities of the steel in actual service, and, of course, are of no assistance whatever in judging the suitableness of the steel for such purposes as taps, chasers, blanking dies and nail-forming tools.

Treatment of High Speed Steels: In any discussion of the quality of high speed steel, the importance of proper treatment after manufacture cannot be over-emphasized. No high speed steel will give its best in service unless it is handled right in forging, in heat treating and in operating the tool into which it is formed. The truth of this statement has always been evident even from the time of Taylor and White's experiments. For this reason the methods of forging and treating these steels are recited here somewhat in detail.

Forging and Machining: High speed steel is usually supplied by the manufacturers in bars of the section required and in an annealed condition, and the first operation in forming is to divide these bars into lengths suitable for the purpose intended. These lengths should always be cut from the bar with a hack saw, but if no hack saw is available, the bar may be heated slowly to a red color, nicked and broken while hot. High speed steel should never be broken cold, because this treatment is liable to start tiny cracks which will not weld in forging and will certainly be enlarged by the subsequent heat treatment. Heating for forging should be done slowly and gradually, for if a cold bar is placed in a hot fire it is liable to be cracked or overstrained by unequal expansive forces. The maximum temperature should not exceed 1090°C. (2000°F.), and hammering after the steel has cooled below 900°C. (1650°F.) should be avoided. As soon as

the forging has been completed, the steel should be covered with lime or other insulating materials to retard the cooling so as to avoid self-hardening. After the steel has become cold, forged tools should be rough ground to eliminate any of the small invisible surface cracks due to forging that frequently occur at or near the cutting edge. Fine tools, such as hobs, small drills, small reamers, taps, milling cutters, etc., cannot be forged to the form required and must be machined from annealed stock. In redressing or forming operations on used tools, the entire tool should first be annealed to eliminate the structures produced by the previous heat treatment. Rehardening without first reannealing such tools causes what is called a "scaly structure" that cannot be eliminated by subsequent heat treatments, and makes the steel brittle and liable to break down in service.

Annealing: After forging and machining, high speed steel should be annealed before it is hardened. This treatment corresponds to the normalizing treatment given carbon and ordinary alloy steels and has for its object the same purpose, but on account of its self-hardening properties, high speed steel cannot be normalized by cooling in air. This annealing is best carried out in the following manner: To avoid oxidation and scaling, the tools are packed in annealing boxes with fine sand, lime, or ashes. After the covers have been sealed on with fire clay, the boxes are charged into an annealing furnace and heated slowly and uniformly to a temperature of about 1950°C. (the usual range is 1550°F. to 1650°F.), when they are allowed to soak for a period of 4 to 10 hours, depending upon the size of the tools and the weight of the charge. The boxes are allowed to cool to blackness in the furnace, then removed and unpacked when cool enough to handle by hand. If oxidation and scaling is not injurious to the article, open furnace annealing is permissible, but both the heating and cooling must be slow and uniform.

Hardening High Speed Steel: The peculiar property of high speed steel that imparts the ability to retain its hardness or cutting edge at high speeds, or high temperatures, is known as **red hardness.** This property is acquired by the steel to a noticeable extent only after it has been heated to a temperature somewhat above 1100°C. (2000°F.) and cooled rapidly. Since the plunging of a cold tool or other article into a region of such high temperature would set up unequal expansion forces that would injure, if not actually disrupt, the metal, the heating is carried out in two operations, known as preheating and final heating, or heating for quenching. In preheating, the practice to be recommended consists in charging the article or articles to be treated into a cold furnace and heating slowly and uniformly to a temperature of about 820°C. (1500 to 1550°F.). In heating for quenching, the preheated articles are transferred to a high temperature furnace that is maintained at the proper temperature for hardening, or, usually, at a temperature somewhat higher than that

required, and allowed to remain there no longer than is necessary to raise their temperature to the desired point for quenching. This point is generally determined from the appearance of the surface of the steel itself, which begins to "sweat," or blister, at the temperatures usually employed in hardening the high speed steels. Tools that cannot be ground after hardening, or other articles that may be injured by scaling, are heated in a bath of molten barium chloride or other suitable salts for the final heating. If baths are used for preheating, care must be exercised to select materials for the bath that will not alloy with, carbonize or corrode the steel. While all the high speed steels are air-hardening, it is customary in some, if not most, of the best shops to quench in oil. In order to eliminate breakage of intricately shaped articles, the initial temperature of the oil is maintained at about 70°C. (160°F.). The volume of oil should be such that the quenching of the steel will not raise its temperature much above 100°C. (212°F.).

The Best Temperature for Hardening depends upon the composition of the steel and the kind of tool being treated. The best hardening temperature for the four main types of high speed steel when used for heavy duty cutting purposes fall within the following ranges:

Low tungsten-high vanadium type.....1230–1260°C. (2250–2300°F.)
High tungsten-low vanadium and low tungsten-cobalt types.....1275–1290°C. (2325–2350°F.)
High tungsten-cobalt type.....1290–1315°C. (2350–2400°F.)

In general, the red-hardness property of high speed steels does not begin to develop until after a quenching temperature of 1000°C. (1832°F.) has been reached, and is not marked up to 1200°C. (2192°F.), after which hardening point the endurance of the tool in cutting at high frictional temperatures increases rapidly as the quenching temperature rises to the point where the steel begins to blister or "sweat." If heated to a higher point or held too long at the high, or sweating, temperature, the steel becomes brittle, due to the fact that grain growth takes place rather rapidly at these high temperatures. High tungsten steels are not as sensitive to heat treatment as low tungsten steels, and may be heated to higher temperatures than low tungsten steels, while the effect of cobalt is to increase the temperature at which both these classes may be and should be quenched. Certain tools, like milling cutters and threading dies or taps, cannot be heated to as high temperatures as other tools, such as rough lathe tools, on account of ruining the fine cutting edges by blistering or pitting. These finer tools may be satisfactorily treated by heating to a temperature but slightly above 1200°C. (2200°F.) and holding at that temperature for a slightly longer period than when the steel is heated to the sweating point. As grain growth takes place rather rapidly at these high temperatures, care must be exercised in regulating the time of soaking to avoid coarsening the grain to such an extent that the steel will be injured thereby.

Tempering and Secondary Hardness: The behavior of hardened high speed steels in tempering is somewhat different from that of the carbon steels or pearlitic alloy steels over the same temperature range, but if the change in properties due to tempering each of these two classes of steel over its own tempering range be compared, the dissimilarity disappears. In tempering the pearlitic steels, whether carbon or alloy, the scleroscope and the Brinell hardness remain constant or increase slightly until a temperature of about 200°C. (392°F.) is passed, when the hardness and brittleness gradually decrease with rise in draw-back temperature until the lower critical point of the steel is reached at about 750°C. (1382°F.) and annealing has taken place. In the case of high speed steels it is found that the hardness remains practically constant or decreases slightly until the tempering temperature reaches 500°C. (932°F.), when the hardness increases rapidly with the temperature to 600°C. (1112°F.), and frequently exceeds that of the quenched steel. After a draw-back temperature of 600°C., or approximately 1100°F., has been exceeded, the hardness of all high speed steels decreases rapidly as the temperature of the draw-back is raised, until a temperature of about 850°C. (1565°F.) is reached, when the steel takes on an annealed state or is in its softest condition, if cooled very slowly. This hardness developed by tempering is known as **secondary hardness,** while the operation is called temper hardening. It is mainly for this reason that many manufacturers and heat treaters recommend a draw-back temperature of 560° to 630°C., or 1050° to 1150°F. Some, however, have obtained good results by drawing back at about 260°C., or 500°F. This success is due to the following reasons: First, secondary hardness, per se, has little effect on the endurance of the steel, which depends mainly upon the quenching temperature. Second, secondary hardness, itself, is closely related to the quenching temperature. In a series of experiments on a high-tungsten-chrome-vanadium steel, for example, it was found that after being quenched from 1900°F. the steel showed no secondary hardness on tempering, but when quenched at temperatures between 2000°F. and 2400°F. the steel showed secondary hardness, and this hardness, as well as the original hardness from quenching, increased as the quenching temperature was raised. Third, the brittleness of high speed steels decreases with the tempering temperature up to about 260°C. (500°F.), remains fairly constant up to 500°C. (932°F.), or in some steels increases, then rapidly decreases again up to 600°C. (1112°F.). The improvement in endurance shown by a highly tempered high speed steel is, therefore, to be attributed to decrease in brittleness as well as to secondary hardness. As to the manner of heating, a salt or lead bath is to be recommended as giving better control of the temperature than an open furnace. The steel may be cooled from the tempering temperature in either air or oil, but never in water.

Metallography: In seeking a better understanding of the very peculiar characteristics exhibited by high speed steels, we naturally turn to the science of metallography. Here we find, that, while high speed

steel has been the subject of many investigations, and much valuable information has been obtained thereby, many of the things that excite our curiosity most are still in the theoretical stage. Under these conditions we do not feel justified in advancing any one theory here, and, as space is not available for even a review of the most important works, we are giving, for the convenience of our readers who may desire to study the subject in detail, a list of what we consider the best and most important original works published on the subject. In addition to Taylor's work already referred to, these articles, in chronological order, are as follows:

1. "The Types of Structure and the Critical Ranges on Heating of High Speed Tool Steels Under Varying Thermal Treatment," by H. C. H. Carpenter. Journal Iron and Steel Institute, No. 1, 1905.

2. "The Function of Chromium and Tungsten in High Speed Steels," by C. A. Edwards. Journal Iron and Steel Institute, No. 2, 1908.

3. "The Chemical and Mechanical Relations of Iron, Tungsten and Carbon," by J. O. Arnold and A. O. Read. Proceedings of the Institute of Mechanical Engineers, 1914.

4. "Effects of Chromium and Tungsten Upon the Hardening and Tempering of High Speed Steel," by C. A. Edwards and H. Kikkawa, Journal Iron and Steel Institute, No. 2, 1915.

5. Tests of High Speed Steels, by M. Yatsevich. Revue de Metallurgie Mémoires. Vol. XV., 1918.

6. "Manufacture and Working of High Speed Steel," by J. H. Andrew and G. W. Green. Journal Iron and Steel Institute. No. 1, 1919.

7. "The Molecular Constitutions of High Speed Tool Steels and Their Correlations with Lathe Efficiencies," by J. O. Arnold and Fred Ibbotson. Journal Iron and Steel Institute. No. 1, 1919.

8. "Note on the Structural Constitution, Hardening and Tempering of High Speed Steel Containing Chromium and Tungsten," by Kotaro Honda and Tokijiro Murakami. Journal Iron and Steel Institute, No. 1, 1920.

9. "Relation of High Temperature Treatment of High Speed Steel to Secondary Hardening and Red Hardness," by Howard Scott. Bureau of Standards Scientific Paper 395, or American Society for Steel Treating. Vol. I. No. 9, 1921.

10. "The Metallography of High Speed Steel," by J. P. Gill and L. D. Bowman. Transactions of American Society for Steel Treating. Vol. 11. Dec., 1921.

11. "Cause of Red Hardness of High Speed Steel," by Edgar C. Bain and Zay Jeffries. The Iron Age, Vol. 112, No. 13, Sept. 27, 1923.

12. "The Nature of the Function of Chromium in High Speed Steel," by E. C. Bain and M. A. Grossmann. Transactions of American Society for Steel Treating, Vol. VI. Oct., 1924.

For the convenience of those who cannot make so detailed a study of the subject, the most important facts of practical value with respect to modern high speed steels that are revealed by these studies may be summed up as follows:

Thermal Critical Points: If a modern high speed steel is carefully annealed, then subjected to tests to determine its critical points, it is found that,

1. On heating slowly and uniformly the steel gives evidence of two thermal critical points, one beginning at about 760°C. (1400°F.) and the other at about 835°C. (1535°F.). These points are remarkably constant for each type of steel and are practically the same for the different types. The second, or upper point, is much more intense than the lower one and is prolonged through a much greater range of temperature.

2. On cooling, these points are affected by the temperature from which cooling begins, by the time the steel is held at that temperature, and by the rate at which the cooling is effected. If the cooling is slow, such as that obtained by furnace cooling, and the steel is not soaked at the maximum temperatures longer than is necessary for uniform heating, cooling from 900°C. (1650°F.) gives only one marked point at about 750°C. (1382°F.); but when the cooling begins from about 980°C. (1704°F.), a second point makes a faint appearance between 375° and 430°C. (700° and 800°F.); and as the maximum temperature to which the steel is heated is raised above 930°C. this lower point increases in intensity and the upper point is still well pronounced; while if the cooling of the steel heated to the higher temperatures is hastened, say at a rate of about 100°C. per minute, the upper point is diminished and lowered and the lower point is much intensified and drops to about 300°C. (572°F.). These facts show that as the upper point on cooling is suppressed, the lower point is intensified, and indicate that the upper transformation on heating becomes the lower transformation on cooling. Also, by heating the steel to a high temperature and cooling rapidly, as in an air blast or in oil, both the transformations may be suppressed, or lowered to a point below atmospheric temperatures.

Chemical Constituents of Annealed High Speed Steel: As to just how the different elements are combined in annealed high speed steel there is still considerable difference of opinion (See references 7, 8, 9, 10 and 11). Arnold and Ibbotson(7), by an electrolytic method, have separated the tungstides and carbides from the remainder of the steel, obtaining these compounds as a residue. Upon analysis, the residue obtained from the steel of the high tungsten-low vanadium type was found to contain approximately 97 per cent. of the total carbon in the steel, 93 per cent. of all the tungsten and vanadium and 27.5 per cent. of all the chromium. When the percentages of the elements in the residue were calculated to combined forms, the composition of the residue was found to correspond closely to

the formula 2 Cr_4C+3 V_4C_3+16 WC+30 Fe_2W. As the residue contained only 27.5 per cent. of the total chromium in the steel, it is to be assumed that the remainder is alloyed with iron, so that, chemically, annealed high speed steel may be considered as a mixture of iron-chromium alloy, chromium carbide, Cr_4C, vanadium carbide, V_4C_3, tungsten carbide, WC, and iron tungstide, Fe_2W. or Fe+Cr+Cr_4C+V_4C_3+WC+Fe_2W. As to how these different elements are combined structurally, Honda and Murokami(8) state that "In an annealed state, a high speed steel containing about 5 per cent. of chromium, 18 per cent. of tungsten, and, .6 per cent. of carbon consists of iron dissolving tungstide, free tungstide, and carbides, Cr_4C and WC, in a free state." With this statement Gill and Bowman(9) do not agree, maintaining that the tungsten is held in an eutectic alloy of complex composition, which they designate as tungstides, while Bain and Jeffries, with the X-ray spectroscope, find only one carbide pattern, which, being unlike Fe_3C, WC or Fe_2W, they assume to be a double carbide of iron and tungsten capable of retaining varying amounts of chromium and vanadium without changing the type of its crystalline lattice. In view of this uncertainty as to the chemical nature of this segregated mixture containing the carbon, tungsten and portions of other elements, neither the term carbides nor tungstides, signifying definite chemical compounds, seem appropriate to use now, and we shall hereafter refer to them as the carbon-tungsten segregates.

A Metallographic Study of the Metallurgical History of a High Speed Steel reveals many facts which are not only an aid in forming some conclusions as to its constitution but are of great importance in its practical application. The first matter of interest in this connection is the action of different etching reagents. A 4-per cent. nitric acid solution or a saturated alcoholic solution of picric acid containing about 12 per cent. of water is used to develop the structure of the matrix of annealed or hardened and highly tempered specimens. Heat tinting also develops the matrix of annealed high speed steel. For hardened untempered specimens a 6-per cent. alcoholic solution of nitric acid is used. None of these methods have any effect upon the carbon-tungsten segregates, which remain white and uncolored. For coloring these carbon-tungsten segregates, a water solution containing 30 per cent. commercial hydrogen peroxide and 10 per cent. sodium hydroxide or an alkaline solution of potassium ferricyanide (10 gms. KOH or NaOH and 10 gms. K_3 Fe $(CN)_6$ in 100 cc. H_2 O) is used. Both of these reagents color the carbon-tungsten segregates dark brown to black. By the proper use of these etching reagents we are able to observe, with the microscope, the different structures developed by different treatments and to trace some of the constituents from the ingot.

Ingot Structures: In cooling from the molten condition, the carbon and tungsten, with some of the iron, chromium, and vanadium, segregate as a eutectic. This statement is clearly shown to be a fact by photomicro-

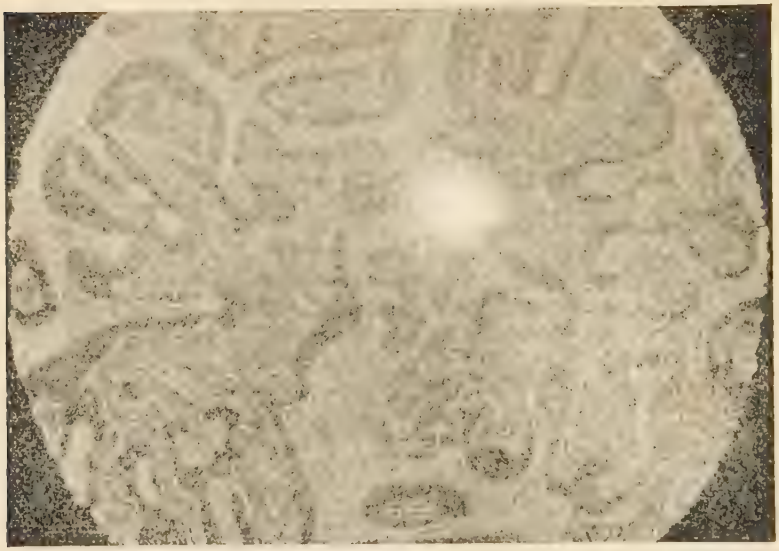


FIG. 216. Photomicrograph No. 1, Showing Structure of High Speed Steel Ingot as Cast x 300 Etched with 4-per cent Nitric Acid.

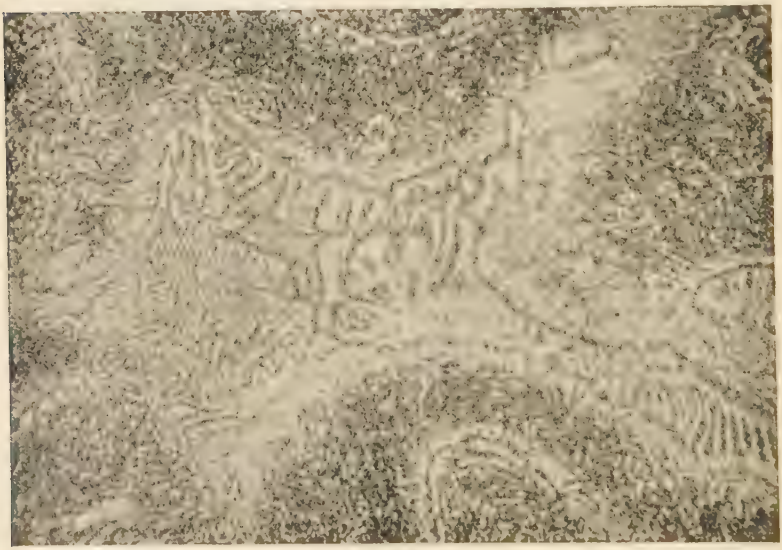


FIG. 217. Photomicrograph No. 2. Showing Structure of High Speed Steel Ingot. x 1100. Etched with Nitric Acid.

graphs No. 1 and No. 2 (Figs. 216 and 217). Here the carbon-tungsten segregates, being unaffected by the nitric acid, remain white in color. Photomicrograph No. 1 shows that the distribution of these segregates gives rise to a cell-like gross structure, while photomicrograph No. 2, at a higher power, shows the spaces within these cells to be filled with the skeleton-like structures characteristic of eutectic mixtures. The first picture indicates that the material immediately surrounding these eutectic areas was the first to solidify, and it is probable that the eutectic mixture was the last to solidify, for Gill and Bowman's experiments indicate that these carbon tungsten segregates are the first to melt on heating.

These carbon-tungsten segregates remain unchanged on heating above the critical range, as is indicated by photomicrographs No. 3 and No. 4 (Figs. 218 and 219), showing the structure of the cast steel after it has been annealed. Number 3 shows that, structurally, the steel is made up of but two constituents, namely, the carbon-tungsten segregates, which appear as light areas unstained by the nitric acid, and a matrix which is etched black. That the carbon-tungsten segregates have retained the characteristics of an eutectic is evident from photomicrograph No. 4, in which they have etched black.

Modifications of the Ingot Structure Produced by Hot Working: Since heating to an annealing or forging temperature has no effect upon the eutectic mixture containing the tungsten, the first effect of working the steel at these temperatures is to break up the cellular structure and cause the carbon-tungsten segregates to assume the form of globules, as shown in photomicrograph No. 5 (Fig. 220). Then, as the working is continued, these irregularly shaped globules are elongated, forming the "stringers" shown in photomicrograph No. 6 (Fig. 221). For reasons which will become apparent later, this is an undesirable structure for finished high speed steel to possess. But by continuing the working and upsetting or otherwise changing the direction of the working repeatedly, these stringers are in turn broken up into the small globules shown in photomicrograph No. 7 (Fig. 222), which is, if the globules are uniformly distributed, the most desirable structure for the steel.

Structural Changes Brought About by Heat Treatment Alone: Annealing the steel leaves the tungsten globules chemically unchanged, as shown by the action of the etching medium used in photomicrograph No. 8 (Fig. 223). If the cooling is very slow, this treatment renders the steel comparatively soft, the Brinell hardness being about 230. Upon heating the steel for hardening, at least two sets of changes take place, as indicated by the two thermal critical points. Although authorities have not yet agreed on the chemistry of the changes, there is reason to believe that the first point marks the change to austenite while the second point marks the beginning of solution of the carbon-tungsten segregates. These tungsten globules are dissolved but slowly; their complete solution

FIG. 218. Photomicrograph No. 3. Showing Structure of Ingot after Annealing. x 500. Etched with 4-per cent. Nitric Acid.

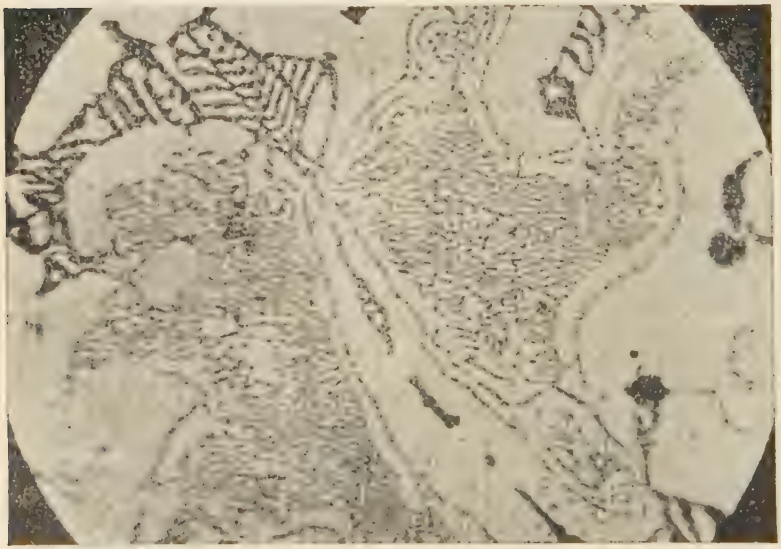


FIG. 219. Photomicrograph No. 4 Showing Structure of Annealed Ingot developed by etching with sodium hydroxide-hydrogen peroxide solution. x 1100.

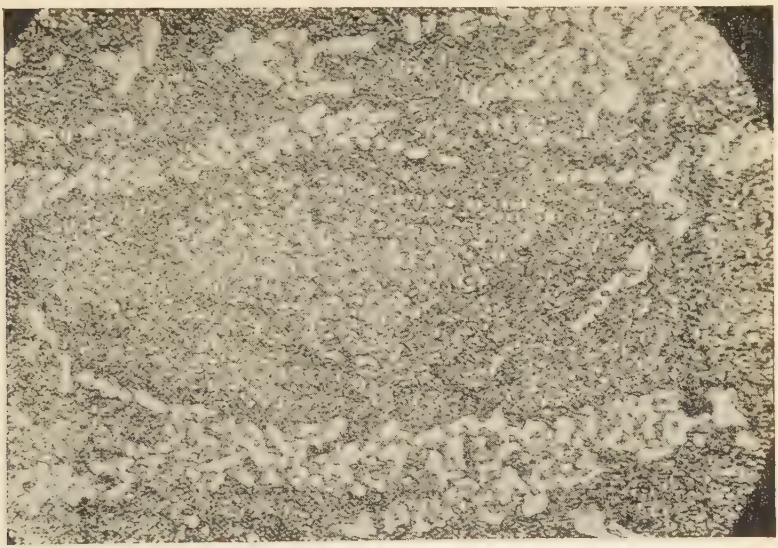


FIG. 220. Photomicrograph No. 5, Showing Structure of Steel Produced by moderate amount of Hot Working. x 275. Etched with Nitric Acid.

FIG. 221. Photomicrograph No. 6, Showing Structure of Steel after Considerable Reduction by Hot Working. x 275. Etched with Nitric Acid.

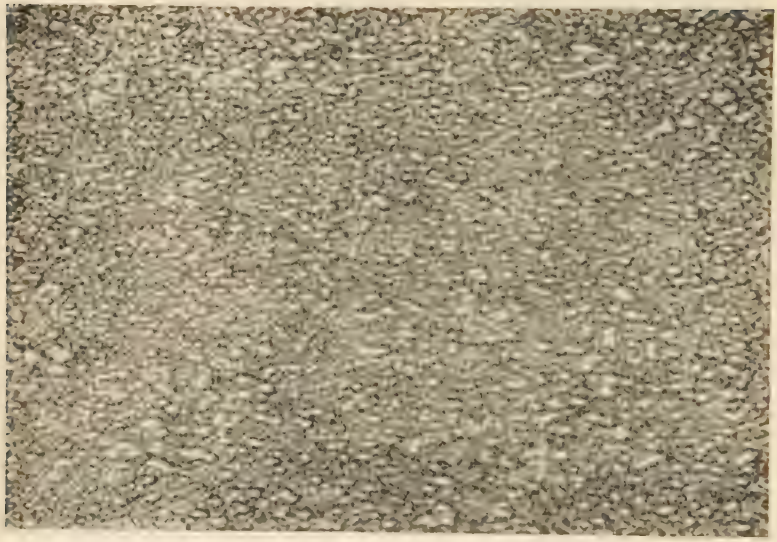


Fig. 222. Photomicrograph No. 7, Showing Structure of Properly Worked Steel, x 500. Etched with Nitric Acid.

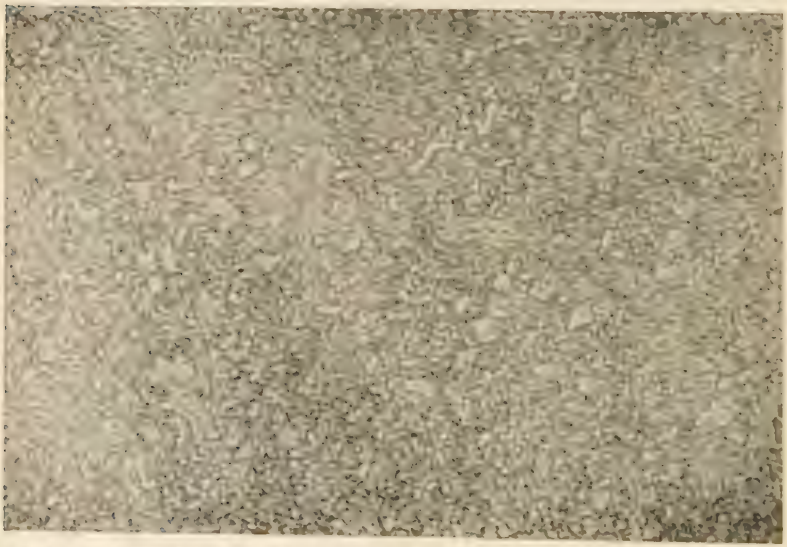


Fig. 223. Photomicrograph No. 8, Showing Structure of Hot Worked and Annealed High Speed Steel, x 500. Etched with Picric Acid.

requires a comparatively long time and a comparatively high temperature. Indeed, when the tungsten content exceeds 12 per cent., they are never all dissolved, at least in ordinary practices. The evidence for these statements is seen in photomicrographs No. 9 and No. 10 (Figs. 224 and 225). Here the etching has colored the tungsten-bearing particles black. The lesser number seen in No. 10 is evidence of the effectiveness of the higher temperature in dissolving these particles.

Photomicrograph No. 11 (Fig. 226) shows the structure of the steel after it has been quenched from the higher temperature. Here are seen the tungsten globules that have not dissolved embedded in a crystalline mass which possesses the polyhedral grain structure characteristic of austenite. At lower magnifications these grains appear to be made up of homogenous metal, but under the highest powers a second constituent that can scarcely be detected at 500 diameters can be discerned embedded in the austenite. According to Bain and Jeffries, this second constituent is martensite. The steel now shows a Brinell hardness of about 600, which is a little less than that of a hardened one-per cent. carbon steel, but the steel is tougher and shows much greater cutting ability. The toughness is characteristic of austenite, while the cutting efficiency is due to the martensite in the austenite grains and possibly in part to the embedded particles of undissolved carbon-tungsten segregates. As stated by Honda and Murakami: "In tool steels numerous fine and hard globules in a tough ground mass will behave like saw-teeth and increase the cutting efficiency of the tool." But it is probable that much of this peculiar hardness is due to the presence of martensite, which, through slip interference, may greatly increase the resistance of the austenite grains to deformation.

Structural Changes on Tempering: A study of the structural changes that occur on tempering, helps to explain both the red hardness and the secondary hardness of high speed steel. Upon reheating the quenched steel to a temperature of from 500°C. to 600°C. (932°F. to 1100°F.) the austenitic structure disappears and is replaced entirely by a martensitic structure, as shown in photomicrograph No. 12 (Fig. 227). The iron-chromium alloy of the martensite thus formed is extremely fine grained, and as the change is accompanied by the precipitation, or separation, of the dissolved carbon and tungsten in finely divided form, thus giving a tremendous key effect, the metal becomes still harder, the Brinell hardness increasing to about 650. This martensite is not so brittle as that formed by quenching other steels, because the conditions of its formation relieve all strains in the steel and make it a stable constituent at temperatures which destroy the martensite of pearlitic steels.

Heating beyond 590°C. (1100°F.) causes the hardness to decrease rapidly until at about 785°C. (1450°F.) the Brinell hardness is only about 350 and the martensitic structure is replaced by another which may be

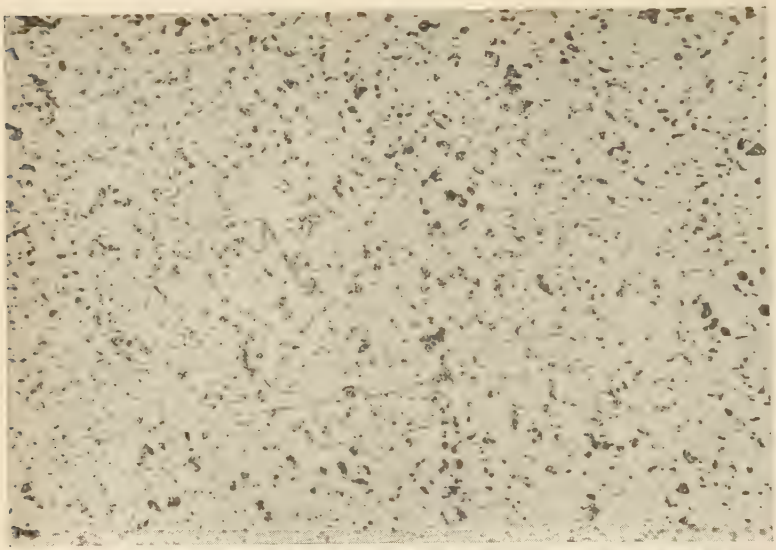


FIG. 224. Photomicrograph No. 9, Showing Carbon-Tungsten segregates in High Speed Steel Quenched from 2100° F. x 250. E. Etched with Sodium Hydroxide-Hydrogen Peroxide Solution.

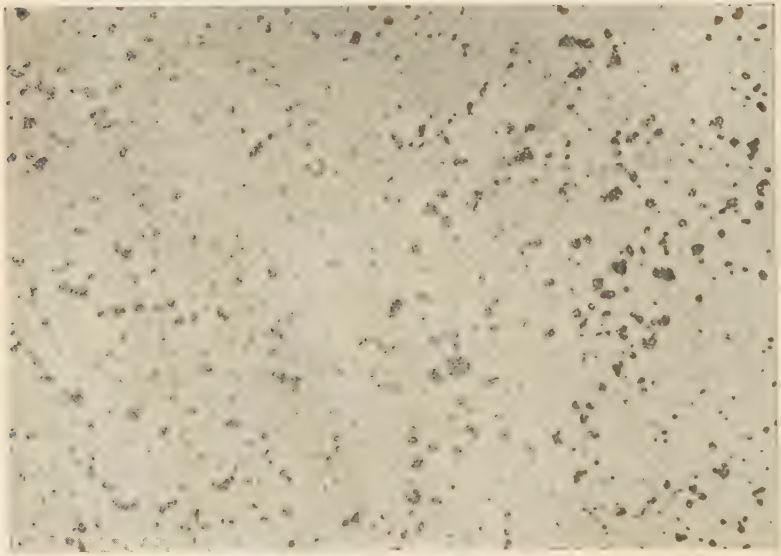


FIG. 225. Photomicrograph No. 10, Showing Same as No. 9, but Quenched from 2380° F.

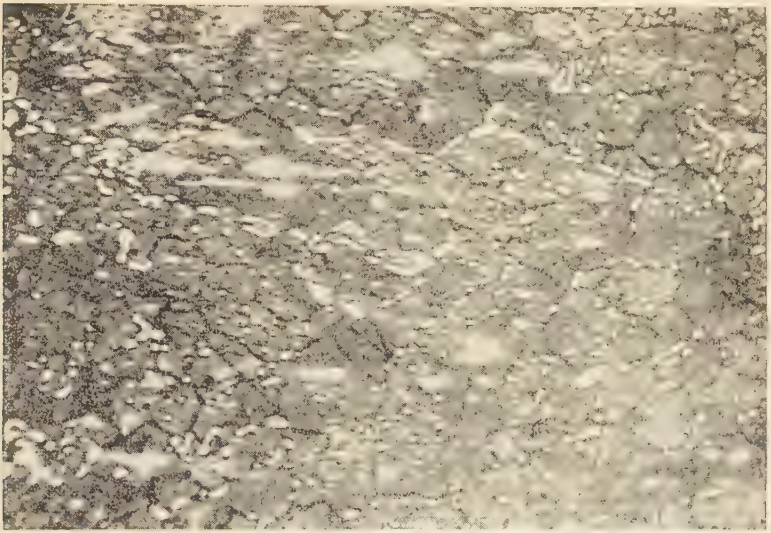


FIG. 226. Photomicrograph No. 11, Showing Structure of Oil Quenched High Speed Steel. x 500. Etched with Alcoholic Nitric Acid.

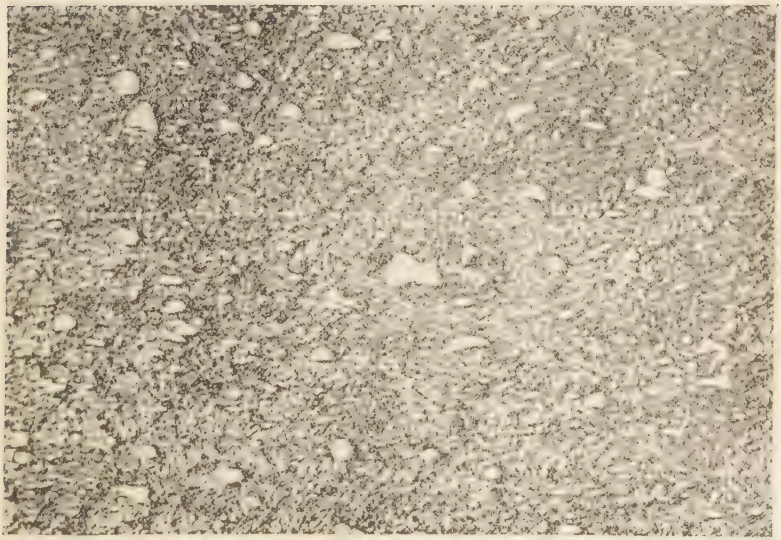


FIG. 227. Photomicrograph No. 12, Showing Structure of Hardened High Speed Steel after being tempered at 1100° F. x 500. Etched with Nitric Acid.

called troostite. Heating to a still higher temperature, or but slightly above the upper critical point, and cooling slowly decreases the Brinell hardness to about 230, but the structure cannot be distinguished from that of troostite. Since this phase follows martensite and troostite and shows none of the charactertistics of the pearlite of ordinary carbon steels it is called sorbite. Sorbite represents the end of the transformation from austenite and the stable constituent for high speed steel, for even the most careful annealing fails to develop a structure that can be distinguished from that obtained as described above.

When high speed steel is air-hardened, the slower rate of cooling, especially in the case of large sections, permits a partial transition, so that the hardened steel exhibits some of the properties of both austenite and martensite. Complete austenization of the steel is to be obtained only by heating to the point of incipient fusion and quenching, or by soaking for a longer time at a somewhat lower temperature and quenching. As the latter method induces grain growth, it is never used in practical work. When a high speed steel tool is given a low draw back treatment after hardening, the frictional heat generated when the tool is put into service, instead of softening it, tends to change the austenite to martensite, more or less completely near the cutting edge, so that this tool is harder and gives better service after the first grinding than before.

The Functions of Carbon, Chromium and Tungsten in High Speed Steel: As previously indicated, the elements essential to impart high speed properties to steel are carbon, chromium and tungsten. Without attempting to discuss the chemical reactions that may take place between the different carbides and tungstides on heating the steel above the critical range, which, according to some investigators, are of a very complex character, the student will find that a review of certain facts will lead to some interesting conclusions. A .70-per cent. carbon steel, water quenched from a temperature but slightly above its critical range, gives a Brinell hardness of about 550 and a martensitic structure, and shows little resistance to tempering. A steel of similar carbon content, but containing 3.50 to 4.00 per cent. chromium, hardens in air from a temperature of 900°C. (1650°F.); and if it is quenched in oil, it is extremely hard, shows a martensitic structure, and offers considerable resistance to tempering. The same remarks apply to stainless steel, which contains half as much carbon and about three times as much chromium, except that it is less hard. The microstructure of these steels after hardening contains no carbide or other particles corresponding to the carbon-tungsten segregates of high speed steel, which fact indicates that the chromium and carbon in these steels are wholly dissolved in the iron. In none of these three steels is the position of the critical points on cooling influenced by the temperatures above the critical from which cooling begins. A steel with a carbon content of .70 per cent. and a tungsten content of 15.00 to 18.00 per cent. is not self-harden-

ing, gives a Brinell hardness of about 500 when quenched in oil from 1100°C. and shows some resistance to tempering with a slight secondary hardness. Gill and Bowman state that in such a steel most of the carbon-tungsten segregates remain undissolved regardless of the temperature, short of actual fusion, from which the steel is quenched. As pointed out in other parts of this section, the maximum temperature to which such a tungsten steel is heated above its first critical points does influence the position and even the number of the critical points on cooling. Now, it will be recalled that Arnold and Ibbotson found only a part of the chromium of high speed steels in the carbide and tungstide residues, hence the remainder must be in the matrix and alloyed with iron. In these steels, it has just been shown that the carbon-tungsten segregates are dissolved more and more as the temperature rises above the upper critical point or as the time at which the steel is held at a given temperature above that point. From these observations we conclude that iron containing chromium in solution has the power of dissolving a greater proportion of these tungsten-bearing segregates than iron alone. It is this tungsten dissolved in the iron-chromium alloy, that, added to the influence of the dissolved carbon, suppresses the transformations and makes it possible to obtain the steel in the austenitic condition by quenching.

Manufacture of High Speed Steel: High speed steel can be made only by the crucible or electric furnace processes. When made by the crucible process high grade wrought iron scrap, or muck bar, high speed steel scrap, ferro-chromium, ferro-tungsten, ferro-vanadium and charcoal are the principal raw materials. These materials are carefully weighed out in portions according to a well-proven formula and charged into the crucible, with the ferro-alloys, particularly the ferro-tungsten, on top. On account of its great weight, the ferro-tungsten will not mix well with the melt if placed at the bottom of the charge. This charge is "dead melted," "pulled" and cast in the usual way. When the steel is made in graphite pots, it is difficult to control the carbon, as the amount absorbed varies greatly, and control of the carbon is an important matter in high speed steel. Clay pots may be used, but only about half as much steel can be charged in a pot, as they are not strong enough to support the weight of a large charge, and only one-fourth as many heats can be made in one pot.

The Electric Process, while not as simple as the crucible, offers certain advantages over the older method that are rapidly making it the chief process for the manufacture of fine steels and have led to its adoption by more than three-fourths of the tool steel makers of this country. In order to provide for the removal of phosphorus and sulphur, a basic lined furnace is always employed. The raw materials used vary somewhat in different localities. The accompanying charge sheet shows the materials used in a 3-ton Heroult furnace, and may be taken as typical of best American practice.

Table 95. Charge for High Speed Steel Made in 3-Ton Heroult Electric Furnace.

Chemical Specifications.

C.	Si.	Mn.	S.	P.	W.	Cr.	V.
.65/.75	.10/.35	.10/.30	.03 max.	.03 max.	17.50/18.50	3.75/4.25	.85/1.20

Raw Materials and Product.

Charged	Lbs.
High Speed Steel Bar Ends	2200
High Speed Steel Scrap	600
High Speed Steel Turnings	400
Low Tungsten Steel Scrap	300
Ferro-Silicon	35
Ferro-Manganese	5
Ferro-Chrome-High Carbon	228
Ferro-Tungsten	984
Ferro-Vanadium	105
Wrought Iron or Muck Bar	2300
Limestone	250
Lime	150

Produced

Ingots Cast		Scrap
No.	Size	Ingots 800 lbs.
4	6″	
8	7″	

Time for Heat.

Power on, 7:50 A. M.

Tapped, 2:25 P. M.

Chemical Analyses.

Test No.	C.	Si.	Mn.	S.	P.	W.	Cr.	Va.
1	.42					17.03	3.03	.35
2	.48							
3	.59							
Final	.69	.27	.35	Trace	.018	17.90 17.92	3.77 3.78	1.06

All the materials shown are charged at the beginning excepting the lime and the ferro-manganese, ferro-chrome, ferro-silicon, and ferro-vanadium. Due to their rapid oxidation, these ferro-alloys are not added until after melting and refining have been accomplished. To prevent great fluctuations in the current during the melting period, the fine turnings are placed directly beneath the electrodes.

As soon as the charge is thoroughly melted, a sample of the steel is taken for analysis; lime is added; additions are made to give the composition desired; and, as soon as the steel is dead-melted, the manganese, chromium, silicon and vanadium are added. After these additions have melted and diffused into the bath, the steel is poured into a ladle from which it is teemed into split moulds by top pouring. Each of these moulds is provided with a hot top made of refractory clay, which is heated to a white heat and placed on the surface of the steel just as the mould is filled. This top, which is of a smaller section than the top of the ingot, is then filled with the steel to act as a feeder to fill up the pipe. After casting into ingots, the steel is cooled slowly to prevent clinks in the ingots, the top part, or sink head, is broken off, and the ingots are then stored for future use.

Distribution of the Carbon-Tungsten Segregates: From what has been said in connection with the metallography of high speed steel, it will be evident that size and distribution of the carbon-tungsten segregates are matters of great importance. The desired fineness, or size, and the uniform distribution of these segregates can be secured by keeping the casting temperature low, by limiting the size of the ingot and by properly working the steel. Attention has already been called to the fact that the gross structure of the ingot is somewhat cell-like in character. On further examination this cell structure is found to be finest about the outer periphery of the ingot, and coarsest at the center, a condition that is evidently due to differences in the rates of cooling. From this fact it is apparent that small ingots, by solidifying rapidly, will have a more uniform and a finer structure than large ingots, and ingots cast at a low temperature will have a better structure than those cast at a high temperature. These are matters that must receive careful consideration especially in connection with the electric process, which tempts the manufacturer to use as large ingots as practicable. However, a large ingot permits a greater amount of work to produce a finished bar than the small ingot, and the greater the amount of reduction the better will be the size and distribution of the tungsten-bearing globules, which result neutralizes the effect of the slow cooling and greater segregation in the larger ingot. As to the best method of working, some consider rolling as good as forging. Since rolling works the steel mainly in one direction it would seem to favor the development of an undesirable "stringer effect." Hammer forging, provided the hammer is heavy enough to cause the effects of each blow to penetrate deep into the ingot, should break up the structure more effectively. Besides, this method of working gives opportunity for close inspection of the steel and frequently discloses defects which may be eliminated during the operation.

Forging and Rolling: Since, for the reason just cited, it is difficult to secure results necessary in a product of highest quality by rolling or pressing, high speed steel ingots are, with but few exceptions, cogged into

blooms and billets by hammer. The cold ingots are first preheated then heated to a temperature of 2000°F. from which temperature they are forged into billets or into finished blocks ready to be annealed and machined. During this operation careful attention must be given to the hammering, and the steel must be watched closely for defects. A large number of fairly light blows with a hammer will produce a better structure than a small number of very heavy blows. After the forging has been completed, it is necessary to cool the steel very slowly to prevent "clinks," or cracks, from developing. This cooling is generally effected by plunging the forged piece into lime or fine hot ashes or loam. When cold, the steel is carefully inspected, and all discoverable defects are eliminated by discarding or grinding. The billets are next reheated to a temperature of about 2000°F. and rolled into the desired shapes and sizes. In rolling, the reduction per pass must not be too great, and the bars must be finished before the temperature has dropped below 840°C. (about 1550°F.). Otherwise, the rolling of high speed steel presents no difficulties not encountered in ordinary steel.

Annealing: All finished high speed steel is box annealed at the works. For bars, the containers are usually large pipes in which the bars are packed with lime or fine sand, or a mixture of carbonaceous material and lime or sand, to prevent the oxidation and decarburization of the bars. After sealing, the containers are charged into an annealing furnace, which should be at a temperature of less than 500°C. or 900°F. The temperature of the annealing furnace is now slowly raised until it reaches 845°C., or 1550°F., and the temperature is held between this point and 930°C., or 1700°F., for a period of from six to twelve hours. The containers are allowed to cool in the furnace at a rate of about 30°F. per hour until the temperature is below 540°C. or 1000°F. when they are removed and cooled in the air to a point where the material can be handled by hand. After unpacking, each bar, piece or article is most carefully inspected, when it is ready to be shipped to the tool maker or consumer who fashions it and treats it for its career as one of the great marvels of the age of steel.

Part IV.

THE MANUFACTURE OF STEEL WIRE, SHEET AND TUBULAR PRODUCTS.

CHAPTER I.

GAGES.

Meaning of the Word Gage: In the metal trades the word gage, or gauge, is a term used in connection with various systems, or scales, for expressing the thickness or weight per unit area of thin plates, sheets, or strips, or the diameters of rods or wires. Specific diameters, thicknesses, or weights per square foot are denoted in gage systems by certain numerals prefixed to the word, as No. 12 gage, No. 20 gage, No. 30 gage or simply as 12 gage, 20 gage, 30 gage, etc. Gages are used only in connection with light materials, that is, when the thickness is not more than one-quarter inch or the weight per square foot is not more than 10 pounds, though most gage tables begin at about ½ inch, or 20 pounds per square foot, and one table begins at double these quantities. Heavier and thicker materials are always denoted by weight per unit area or length, or by thickness, in customary or metric units.

Origin of Gages: This custom of indicating thickness and diameter by gage numbers originated in the early days of the metal industries, and the gage numbers were probably at first employed to designate the different sizes that could be most readily produced by different stages, or steps, in the processes of manufacture. As the processes of manufacture varied more or less, not only for different lines, but often amongst different manufacturers of the same line, and as an individual system of measurement was often considered a trade advantage, there finally appeared a great number of gages. It has been said that at one time there were in this country and England more than fifty different wire gages in use, and several distinct gages for sheets. This fact alone would give rise to considerable confusion, but, as if confusion were to be sought rather than avoided, different names were often applied to the same, or practically the same, gages, and the same names to different gages; and symbols, as W. G., B. W. G., G., U. S. G., rather than names, were employed to indicate the

particular gage system meant. All those gages were not only dissimilar with respect to each other in actual thicknesses denoted by the gage numbers, but the different gage numbers in the same gage table seldom bore any mathematical relation to each other.

Relation of Gage Number to Thickness: Those gages had but one characteristic in common, namely, that the higher the gage number the thinner was the material. This relation of gage numbers to actual thickness has always been maintained, and the association of high gage number with thin material or with small diameter has become fixed, by long custom, in the minds of the people. This fact has contributed largely to the defeat of all attempts to simplify gages by making the gage numbers represent thousandths of an inch. With but few exceptions this relation of gage number to thickness or diameter persists to the present time. In the Sheet Zinc Gage, Belgian Zinc Gage, Paris (French) Gage, and Music Wire Gage, the gage numbers increase with the thickness of the sheet or the diameter of the wire.

British Gages: Chief among these early gages were the Birmingham gages, one for sheets and another for wire. Then came Stubs' gages. As Stubs was from Warrington, his most popular gage was often called the Warrington Wire Gage, and also Peter Stubs' Gage. In this country Peter Stubs' Gage is commonly taken to be identical with the Birmingham Wire Gage. Stubs is, perhaps, to be credited with the first attempt at reform in gages, as he gave the equivalents of his gage numbers in decimals of an inch. The first organized attempt, however, at revising gages was made by the English in 1883. In that year the British Board of Trade prepared a gage which was intended as a standard for both wire and sheets, but is now known as the British Imperial Standard Wire Gage, designated in the British Empire by the initials W. G. or B. W. G. and in the United States by the initials I. S. W. G., to distinguish it more readily from the Steel Wire Gage (Stl. W. G.). This gage became the legal British standard gage March 1st, 1884. As the Imperial Standard Wire Gage was found to be unsuitable for sheets, the use of a new gage, which was a revision of the old sheet gage, was permitted. This gage came to be known as the Birmingham Sheet and Hoop Iron Gage, and was represented by the symbols B. G. In England it was used as a standard gage for sheets by common consent until July 16, 1914, when it was established legally as the British Standard Gage for Iron and Steel Sheets and Hoops, B. G. The Birmingham Wire Gage, B. W. G., or Stubs Warrington Wire Gage, has fallen into disuse. Custom gages for galvanized sheets now usually have B. G. suffixed to the numbers but the weights have no systematic relation to the weights of B. G. for uncoated sheets.

U. S. Sheet Gages: The next attempt at standardizing gages was made in the United States after the passage of the McKinley Bill in 1890. By an Act of Congress, approved March 3, 1893, the United States Standard

Gage for Sheet and Plate Iron and Steel (U. S. S. G.) was established as the only standard gage for these materials after July 1st, 1893. This gage is a weight gage. It is based upon weights per square foot in pounds avoirdupois beginning with 20 lb., No. 7/0's gage, and ending with .25 lb., No. 38 gage. Other weights per unit area, in customary and in metric units and combinations thereof, were established on the basis of the legal equivalents; and the approximate thicknesses were determined from the density of wrought iron, which is 480 pounds per cubic foot, or .2778 pound per cubic inch. On this basis the equivalent thickness for each gage can readily be expressed both as a common fraction and a decimal fraction of an inch. Since the adopted standard density for steel is 489.6 pounds per cubic foot or .2833 pound per cubic inch, the thickness equivalents for steel are slightly less than those for wrought iron. This change is legal because the governing factors in the gage schedule are weights and not thicknesses. While the gage as established by Congressional enactment was limited on the light side to .25 lb. per square foot, or No. 38 gage, it has since been extended by custom to .1875 lb. (3 oz.) per square foot, or No. 44 gage. In this country the gage is standard for all uncoated sheet and plate iron and steel, though it is used only in No. 3 (10 lb. per sq. ft.) and lighter. It is also used for long terne plate and, especially in the lighter gages, for tin plate. The Galvanized Sheet Gage, established by custom, is based on the U. S. S. Gage, each gage number of the Galvanized Sheet Gage being 2.5 ounces per square foot heavier than the same U. S. S. Gage number.

The Tin Plate Gage: For tin and small terne plate long custom has established the Tin Plate Gage, which is practically the same for both this country and England. This gage is expressed, not in gage numbers, but in pounds per base box. By base box is meant 112 sheets each 14 x 20 inches, or other number and size of sheets that will cover an area of 31360 square inches. In former times the gages of tin plate were designated by symbols and names, as IC (Common), IX (X or Extra), DC (Double Common), 2 X (two—X), ICL (Lights), corresponding respectively to 107 lb., 135 lb., 139 lb., 155 lb., 100 lb., per base box, etc. In these symbols each X stood for a certain additional weight, and L for a certain decrease in weight. This custom is still used to designate some weights of tin plate, but these symbols now mean little as standards, and internationally they mean nothing at all. The use of these symbols is decreasing, and in time they should be abandoned altogether.

U. S. Wire Gages: Wire gages have never been legally standardized in the United States, but steel wire practice in this country resulted in the adoption by different manufacturers of gages that were practically alike. Chief among these gages were the American Steel & Wire Company's gage, Washburn and Moen's gage, and Roebling's gage, all of which were very nearly the same. Therefore, upon recommendation of the Bureau of Standards, this gage is designated as the Steel Wire Gage, Stl. W. G.,

Table 96. Showing Relations of Chief American Gages.

WEIGHT GAGES								THICKNESS GAGES				
Name of Gage	United States Standard Gage, U. S. S. G.		Galvanized Sheet Gage, G. S. G.		Tin Plate Gage, T. P. G.			Steel Wire Gage, U. S. Stl. W. G. Stl. W. G.	Music Wire Gage, M. W. G.	Brown & Sharpe Gage, B. & S. G. A. W. G.	Stubs Iron Wire Gage, W. W. G. B. W. G.	Name of Gage
Principal Use	Uncoated Steel Sheets and Light Plates		Galvanized Sheet Steel		Tin Plate			Steel Wire, except Music Wire	Steel Music Wire	Non-ferrous Sheets and Wire	Bands, Hoops and Wire	Principal Use
Gage No.	Equivalent Thickness, Inch	Lb. per Sq. Ft.	Lb. per Sq. Ft.	Oz. per Sq. Ft.	Lb. per Sq. Ft.	Lb. per Base Bx.	Symbol	Thickness, Inch	Thickness, Inch	Thickness, Inch	Thickness, Inch	Gage No.
7/0's	.4902	20.0000						.4900				7/0's
6/0's	.4596	18.7500						.4615	.004			6/0's
5/0's	.4289	17.5000						.4305	.005		.500	5/0's
4/0's	.3983	16.2500						.3938	.006	.4600	.454	4/0's
3/0's	.3676	15.0000						.3625	.007	.4096	.425	3/0's
2/0's	.3370	13.7500						.3310	.008	.3648	.380	2/0's
0	.3064	12.5000						.3065	.009	.3249	.340	0
1	.2757	11.2500						.2830	.010	.2893	.300	1
2	.2604	10.6250						.2625	.011	.2576	.284	2
3	.2451	10.0000						.2437	.012	.2294	.259	3
4	.2298	9.3750						.2253	.013	.2043	.238	4
5	.2145	8.7500						.2070	.014	.1819	.220	5
6	.1991	8.1250						.1920	.016	.1620	.203	6
7	.1838	7.5000						.1770	.018	.1443	.180	7
8	.1685	6.8750	7.0312	112.5				.1620	.020	.1285	.165	8
9	.1532	6.2500	6.4062	102.5				.1483	.022	.1144	.148	9
10	.1379	5.6250	5.7812	92.5				.1350	.024	.1019	.134	10
11	.1225	5.0000	5.1562	82.5				.1205	.026	.0907	.120	11
12	.1072	4.3750	4.5312	72.5				.1055	.029	.0808	.109	12
13	.0919	3.7500	3.9062	62.5				.0915	.031	.0720	.095	13
14	.0766	3.1250	3.2812	52.5				.0800	.033	.0641	.083	14
15	.0689	2.8125	2.9687	47.5				.0720	.035	.0571	.072	15
16	.0613	2.5000	2.6562	42.5				.0625	.037	.0508	.065	16
17	.0551	2.2500	2.4062	38.5				.0540	.039	.0453	.058	17
18	.0490	2.0000	2.1562	34.5				.0475	.041	.0403	.049	18
19	.0429	1.7500	1.9062	30.5				.0410	.043	.0359	.042	19
20	.0368	1.5000	1.6562	26.5				.0348	.045	.0320	.035	20
21	.0337	1.3750	1.5312	24.5				.0317	.047	.0285	.032	21
22	.0306	1.2500	1.4062	22.5				.0286	.049	.0253	.028	22
23	.0276	1.1250	1.2812	20.5	1.1250			.0258	.051	.0226	.025	23
					1.079	235	6X					
					1.047	228	6XL					

24	.0240	1.0000	1.1562	13.5	1.0000			.0230	.055	.0201	.022	24
					.987	215	5X					
					.964	210	D2X					
					.955	208	5XL					
					.895	195	4X					
25	.0214	.8750	1.0312	16.5	.8750			.0204	.059	.0179	.020	25
					.863	188	4XL					
					.827	180	DX					
					.804	175	3X					
					.771	168	3XL					
26	.0184	.7500	.9062	14.5	.7500			.0181	.063	.0159	.018	26
					.748	163						
					.712	155	2X					
27	.0169	.6875	.8437	13.5	.6875			.0173	.067	.0142	.016	27
					.680	148	2XL					
					.657	143						
					.638	139	DC					
28	.0153	.6250	.7812	12.5	.6250			.0162	.071	.0126	.014	28
					.620	135	IX					
					.588	128	IXL					
					.574	125						
					.565	123						
29	.0138	.5625	.7187	11.5	.5625			.0150	.075	.0113	.013	29
					.542	118						
					.514	112						
					.505	110						
30	.0123	.5000	.6562	10.5	.5000			.0140	.080	.0100	.012	30
					.491	107	IC					
					.459	100	ICL					
31	.0107	.4375	.5937	9.5	.4375			.0132	.085	.0089	.010	31
					.436	95						
					.413	90						
32	.0100	.4062	.5625	9.0	.4062			.0128	.090	.0080	.009	32
					.390	85						
33	.0092	.3750	.5312	8.5	.3750			.0118	.095	.0071	.008	33
					.367	80						
34	.0084	.3437	.5000	8.0	.3437	75		.0104	.100	.0063	.007	34
					.321	70						
35	.0077	.3125			.3125			.0095	.106	.0056	.005	35
					.298	65						
36	.0069	.2812			.2812			.0090	.112	.0050	.004	36
					.276	60						
37	.0065	.2656			.2656			.0085	.118	.0045		37
					.253	55						
38	.0061	.2500			.2500			.0080	.124	.0040		38
39	.0057	.2344			.2343			.0075	.130	.0035		39
40	.0054	.2187			.2187			.0070	.138	.0031		40
41	.0052	.2109			.2109			.0066	.146	.0028		41
42	.0050	.2031			.2031			.0062	.154	.0025		42
43	.0048	.1953			.1953			.0060	.162	.0022		43
44	.0046	.1875			.1875			.0058	.170	.0020		44

or the United States Steel Wire Gage, U. S. Stl. W. G., as standard for all steel wire other than music wire. For all sheets and wire, of other metals than iron and steel, the Brown and Sharpe (B. & S. G.), or American Wire Gage (A. W. G.), is recognized as standard in the United States. It was prepared at the request of leading manufacturers in this country by Messrs. Brown and Sharpe, of Providence, R. I. The sizes included in this gage range from .46 in. (No. 4/0's) to .005 in. (No. 36) and each size is .890525 of that of the next larger or 1.122932 of the next smaller. The circular mil gage, sometimes called the Edison Gage, is based on the circular mil, which is the area of a circle one mil (1/1000 in.) in diameter. It was devised to simplify electrical calculations. Other thickness gages in use are the Trenton Iron Company's gages and Stubs' Steel Wire Gage. None of these wire gages have any legal authorization, as the only wire gage so far recognized in Acts of Congress is the Birmingham Wire Gage (B. W. G.), or Stubs' Iron Wire Gage. This gage is also used in this country for the measurement of hoop and other strip steel, but the tendency in these lines is to abandon the use of gages entirely and specify all thicknesses in thousandths of an inch. This gage is being abandoned in the wire field, also.

Caution: While this section is not to be thought of as a full discussion of gages, it is hoped it will at least serve as a guide to the uninitiated in the steel wire, sheet, and strip industries. But most of all it is intended to emphasize the danger of confusion in the use of gages to indicate thicknesses and diameters. This danger is present in domestic, as well as foreign, dealings and is only to be avoided by making specifications as to size to read in inches, centimeters, or millimeters, or weight per square foot or per square meter, or to give the equivalents, in absolute units, of the gage desired. The relations and equivalents of the principal gages in use in the United States at the present time are shown in table 96. While the exact equivalents in many cases extend to the sixth or seventh decimal places, these are carried only to the fourth place in this table. Hence in these cases, notably Brown and Sharpe Gage, and United States Standard Gage, the equivalents are approximations to this extent, but even these approximations are carried out further than should be used practically.

CHAPTER II.

THE MANUFACTURE OF STEEL WIRE AND STEEL WIRE PRODUCTS.

SECTION I.

HISTORY AND IMPORTANCE OF STEEL WIRE.

Historical: In general, wire is a term that may be applied to any metallic shred, thread, or filament, or to any exceedingly slender rod or bar of metal having a uniform cross section. Considering the term in this sense, wire is of very ancient origin. Gold wire is mentioned in the Bible in connection with the sacerdotal robes of Aaron, and was used to form part of a necklace, found at Denderah, which bears the name of the Pharaoh who reigned in Egypt about 2750 B. C. Evidences of the use of wire by the Assyrians and Babylonians as far back as 1700 B. C. have also been found. As to the methods of manufacture used by these ancient peoples, practically nothing is known. The specimens of ancient wire that have been found so far are flat, and it is probable that they were produced solely by hammering.

How, when or of what material round wire was first made is not known. No doubt it was first produced by hammering, but the difficulty of forming a fine round wire by this method probably caused the metal workers, early in the history of the art, to seek some better method. An old Latin manuscript written by Theophilus sometime during the 8th and 9th centuries describes a method of making wire of an alloy of lead and tin, which was cast into an ingot, hammered into a long slender bar and drawn through holes in a wire drawing plate. The draw plate, itself, is described as "a piece of iron three or four fingers wide, smaller at the top and bottom, rather thin and pierced with three or four rows of holes through which wire may be drawn." However, there is reason to believe that the art of wire drawing was known and practiced before this time. The chain armor used by the knights in the great crusades against the Saracens and Turks is thought by many to have been made of drawn wire.

Other authentic records are available to show that wire drawing on a commercial scale was practiced in France in 1270, in Germany in 1350 and in England in 1465. The first wire drawing mill in this country was

built in 1775 by Nathaniel Miles at Norwich, Conn. But, though three other mills, two of which were in Pennsylvania, were started during the next twenty years, none of these appear to have been very prosperous, for in 1820 practically no wire was being made in this country. In 1831, however, the industry was reestablished in this country by Ichabod Washburn of Worcester, Mass., who, with Benjamin Goddard, founded the firm of Washburn, Moen and Company.

Present Importance of Steel Wire Industry: From that date, 1831, the wire industry grew very rapidly. Aside from the great quantities of wire made from other metals, such as copper and brass, the present annual production of steel wire alone is astonishing. For the year 1923 the production of steel wire rod was approximately 3,000,000 gross tons. This tonnage represents about one-twelfth of all the steel produced in the country, and if it were all drawn into No. 16 wire, which is about an average gage, it would have a total length of more than 122,000,000 miles, or enough to girdle this earth about 4912 times. The causes contributing to this growth were many and cannot be discussed in detail here, but they may be grouped or classified about as follows: 1. The great number of purposes to which wire, particularly steel wire, is adapted. 2. Development of inventions requiring great quantities of wire. 3. Improvements in the methods of producing steel and steel wire. It need not be pointed out that these causes are interdependent. New demands stimulated efforts to improve the methods of manufacture, and as these improvements resulted in the bettering and the cheapening of the product, new uses were found for it.

Principal Uses of Steel Wire: The adaptability of wire to the manufacture of household articles of common use needs no exposition here. These articles, including such items as pins, needles, brooms, strainers, hooks, egg-beaters, toasters, etc., are almost indispensable to our comfort. Of the many inventions developed since 1820 and making use of large quantities of wire, only a few of the most important can be mentioned here. The first of these was wire rope. Rope made of bronze or brass wire is known to be of ancient origin, while iron wire rope was used in Europe as early as 1820. The first wire rope manufactured in this country was made in 1840 at Saxonburg, Pa., by John A. Roebling, founder of the firm of John A. Roebling's Sons Company. In 1844 the first telegraph line, extending from Washington to Baltimore, was completed by Professor Morse, but for more than ten years the growth of the telegraph was hampered because the wire essential in the construction of the lines could be procured only in short lengths, which required much time and labor for splicing. The use of crinoline wire, a high-carbon heat treated wire, for hoop skirts has been cited by some as a novel use of the product and as a great boon to the industry, but is better as an example of the unstable character of a business that depends on fashions. Starting about 1860,

this business, for the next ten years, consumed about 1500 tons of wire annually, but suddenly collapsed with the passing of the hoop skirt in 1870. This was not to be the last time that feminine fashions would play a part in the wire industry, for in 1916 some 15,000 tons of wire was being consumed annually in the manufacture of corsets and several hundred tons for hair pins, but in 1924 we see these items disappearing like the crinoline wire. But the collapse of the crinoline wire business was replaced by more staple articles, for in 1868 the first patents were obtained on the use of wire for bale ties and barbed wire for fence. Both these articles came quickly into wide use, the latter article being especially useful in farming the great unwooded lands west of the Mississippi River, which were rapidly being brought under cultivation about this time. By 1876 the development of the telephone had reached the practical stage, and began to create a demand for more wire of the same type used by the telegraph. It was in 1879 that the beneficial effect of sulphur in wire for screw stock was discovered, and the manufacture of machine screw wire was begun. Chas. H. Morgan also began the manufacture of coiled wire springs in this year. In 1884 woven wire fence was first made by machinery. This fence, of which there are now several types, fulfilled all needs that could not be met with barbed wire or straight wire fence and possessed all the advantages of any fence that could be constructed of wood, hence it was soon being used in all parts of the country. In 1851 the first American made wire nail machine was built by Thomas Morton; in 1875 the first steel wire nails were made; and in 1888 the production of the wire nails exceeded that of the cut nail, for the first time. Today, about twenty times as many wire nails as cut nails are made, and about one-fourth of all the steel wire produced is made into nails. Since 1890 no inventions making such unusual demands upon the wire industry have appeared, so that these items, with the two or three exceptions noted, remain the backbone of the steel wire industry. However, innumerable items employing steel wire in smaller quantities have been developed, which, added to the rather rapid growth of these principal lines, have contributed to a continual expansion in the industry. The extent of this expansion can be judged from the fact that the production of steel wire in 1923 was more than twice that for 1903.

Early Method of Manufacture: Turning now to the matter of wire-drawing, itself, we find the methods employed at the time of its introduction into this country were wholly inadequate to meet the demands that were soon to be made upon it. As the Bessemer and open hearth process for making steel were then unknown, practically all wire was made from wrought iron, or the softer metals like copper, brass, bronze, etc. though crucible steel in softer tempers was also used. Practices varied somewhat in different localities, and detailed descriptions of the operations are lacking, but from information gleaned from different sources we picture the process and operations for drawing wrought iron and steel

wire to be about as follows: Starting with a small square bar or billet, the metal was heated and hammered into as small a round as practicable, say ¼ to ⅜ inch in diameter and some 6 to 10 feet in length. One end of this rod was tapered down to a smaller size, a little less than the hole in the die through which the rod was to be drawn. The rod was then scoured bright with a piece of sand stone or other abrasive. In the case of iron and steel, it was early discovered that this cleaning of the rod was not only essential to good work but was well worth the trouble, for the hard scale, when not removed, soon scored the die. Then, the tapered end of the rod was inserted in the proper hole of a draw plate made of cast iron or hard steel, where it was grasped with a pair of tongs attached to a lever, and the rod was drawn through the hole a few inches at a time, about 5 inches at each stroke being the common practice. The lever could be operated either by hand or by water power, and the rod, as it passed through the hole, was generally lubricated with butter or other grease, to facilitate the drawing and save the die as much as possible. After the first draft, the operation was repeated through progressively smaller holes in the draw plate until the wire was drawn to the size desired or until it became too hard and brittle for further drawing. In case the wire was to be drawn to still finer sizes, it was annealed at a red heat, generally in an oven sealed off from the air, after which the thin coat of oxide thus formed was removed by tumbling with a mixture of sand and water, or by immersing the wire for some time in sour beer or fermented barley water. The machine for drawing this fine wire differed somewhat from that used for drawing the rod. The draw plate was mounted on a table or bench in front of a drum or block that could be revolved by means of a hand-operated crank attached to the block direct or through a system of gears. After pointing, the end of the wire was inserted into the die and drawn through by means of tongs, until it could be attached to the drum. Then by revolving this drum, the drawing of the wire could be performed in one continuous operation, the wire being wound about the drum and thus drawn through the die.

Improvements in the Manufacture of Iron and Steel Wire have kept pace with the demands. In connection with this statement it should be noted that the basic principles of wire making have remained unchanged. As already indicated the process consists essentially in drawing a rod or a slender piece of the metal through a tapered hole in some harder material, or successively through a series of such holes. It involves the application of force in the simplest manner, a straight pull, and the use of one of the simplest tools, the wire drawing die. The efficiency of the latter and the simplicity of both these elements have left little room for improvement, and many doubt the possibility of finding a substitute for the process that will do the work so well. The improvements that have been made pertain to the accessory equipment and to the complementary operations, rather than to the process of wire drawing itself. Thus, the need for long

lengths was met not by any radical change in the wire drawing process, but by changing the method of producing the wire rod. As long as the rod was made by hammering, it was too short to coil, or draw with a block; but when the need for long lengths began to be felt, efforts were made to roll the rod; and about 1840 Washburn succeeding in adapting the wire drawing block to coarse wire drawing. This block was power driven, and provided a means not only of applying a greater pulling force continuously to the rod, but also of storing the wire as it was drawn through the die. This development made it desirable to use very long rods, and this demand was met first by the invention of the three high mill about 1857, which was succeeded by the Morgan continuous mill about 1875 and the Garrett rod mill in 1882. Another important development was the substitution of soft steel for wrought iron, made possible by the invention of the Bessemer and the open hearth process for steel making. This change was inaugurated in this country by the Washburn and Moen Manufacturing Company at Worcester, Mass., in 1871. Improvements in handling, cleaning, coating, or lubricating, the rod, and in heat treating and finishing the wire were also made. Many of these developments have proved of great importance, but as their history is somewhat clouded by uncertainties, we shall leave the past and turn to the manufacture of steel wire as it is carried on today.

SECTION II.

CLASSIFICATION OF STEEL WIRE.

Uses of Steel Wire: For sales purposes wire is largely classified according to use. Needless to say, these uses are many and varied and lack of space will not permit a complete enumeration of them here. However, these uses may be grouped under a few main heads, as shown in the following table, which will indicate the most important and some of the more common uses of steel wire.

Table 97. Showing the More Common Uses and Grades of Steel Wire.

I. Nail Wire—Hard or Soft,—round, square, oval, triangular or grooved.

II. Telegraph and Telephone Wire.—Extra best best, best best, or steel.

III. Fence Wire—Plain, Galvanized or Varnished,—round, oval, or flat. Hard or soft. Straight or with tension curves.

IV. Rope Wire—Round, oval, square or triangular—Swedish iron, crucible cast steel, extra strong crucible cast steel, plow steel, improved plow steel.

Table 97. Showing the More Common Uses and Grades of Steel Wire—Continued.

V. Spring Wire—Round or square—Made in several different grades according to use.

VI. Music wire—Piano wire—Mandolin wire—covering wire, etc.

VII. Corset Steel and Dress Stay Wire.

VIII. Miscellaneous and Special Wires.

Aeroplane wire
Armature Binding wire
Auto Spoke wire
Awl Steel wire
Baling and Binding wire
Bicycle Spoke wire
Bird Cage wire
Bolt wire
Bonnet wire
Bookbinder wire
Bottle wire
Brace wire
Broom wire
Brush wire
Cable Armature wire
Can Key wire
Card wire
Chain wire
Clock Gong wire
Clothes Pin wire
Concrete Reinforcing wire
Cotter Pin wire
Cotton Tie wire
Crimping wire
Cushion wire
Drapery wire
Eye Glass wire
Fish Hook wire
Florists' wire
Grape Tie wire
Gun Barrel Stock
Gun Ribs
Hackle Pin wire
Hair Pin wire
Hair Spring wire
Hat wire
Needle wire
Hook and Eye wire
Hose wire
Hutter wire
Jacquard wire
Lace Tip wire
Link wire
Machine Screw wire
Mantle wire
Mattress wire
Needle wire
Netting wire
Optical wire
Pail Bail wire
Phonograph Needle wire
Picture Cord wire
Pin wire
Pinion wire
Poultry Netting
Ramrod Steel
Reed wire
Rivet wire
Safety Pin wire
Screen wire
Sewing Machine Needle wire
Shoe Nail wire
Spooled Market wire
Spindle wire
Stitching wire
Tack wire
Tag wire
Tire wire
Toe Calk wire
Umbrella wire
Weaving wire
Welding wire

Other Ways of Classifying Wire: In order to adapt wire to the many different kinds of service to which it is applied, the manufacturers must have control of certain factors in its manufacture. These factors include the size, the shape, the finish and the temper, or strength and hardness of the wire, and also the method of manufacture and composition of the steel used in making it. Each of these factors are subject to well-defined limitations, but the control of all of them makes it possible to produce wire suitable for any of the purposes indicated. For manufacturing purposes, then, each of these factors may be made a basis for classifying wire.

Kinds and Composition of Steel Used for Wire: While some special grades of wire are still made from Swedish wrought iron, crucible steel is now very seldom, if ever, used. From a metallurgical standpoint some grades could be advantageously made by the electric process, but for economic reasons this process is rarely used for wire steel. Practically all the steel used for wire, then, is made by the Bessemer, the basic open hearth, the acid open hearth, or the duplex process. Each of these processes produces steel best suited to certain purposes, or kinds of wire, which will be pointed out later in the course of this study. Concerning the composition of the steel, alloying elements are rarely added, for, by properly selecting and handling the plain carbon steels in drawing and heat treating, it is possible to develop a range of physical properties broad enough to meet practically every demand likely to be made upon steel wire. Ordinarily the sulphur and phosphorus are kept within the usual limits for each kind or grade of steel, while the silicon, the manganese, and the carbon content is varied according to the physical properties desired. Occasionally the sulphur content will be increased to improve the cutting properties of the steel. For manufacturing purposes wire is divided roughly into two classes based on composition, namely, low carbon and high carbon wires, as each class must be handled in a manner slightly different from the other. The carbon content of the latter class ranges from about .30 to 1.20 per cent.

Wire Shapes: While wire is ordinarily thought of as being round, i. e., with a circular section, it may have any one of an indefinite number of sectional shapes, as required by the particular use for which it is desired. After the ordinary round wire of circular section, the most common shapes are square, hexagon, octagon, oval, half-oval, half-round, triangular and flat. The term flat as used here does not include the so-called flat wire produced by hot and cold rolling operations only. Although it may be made in long lengths and may have a very small section, ranging from one or two thousandths of an inch up in thickness and from one-eighth inch to twenty inches in width, and although it is made by the wire manufacturers in large quantity, this product is more properly called cold rolled strip, for the term wire should be restricted to the cold drawn products.

FIG. 228. Wire Shapes. Photograph of actual cross sections of a number of shape wires, illustrating many of the odd and intricate shapes produced and indicating the kind of work that may be done.

Besides these regular, or symmetrical, shapes, wire is also made in various odd and irregular shapes, some of which are shown in the accompanying illustration.

Sizes of Wires: The size of round wire is determined by its diameter, which is expressed in absolute units, or decimal parts thereof, or by gage numbers. In this country the absolute unit is the inch, and the diameter is obtained by means of a micrometer capable of giving measurements accurate to the thousandth of an inch, at least. The gage of wire is determined usually by means of an instrument known as a V-gage. As stated in the section on gages, there are several different gages in effect for the measurement of wire. The size of music wire is expressed in gage numbers of a system known as the Music Wire Gage (M. W. G.), which is the standard for this wire. For iron and steel telephone and telegraph wire, the standard gage is the Birmingham Wire Gage (B. W. G.), while for copper electrical wire the Brown and Sharpe Gage (B. & S. G.), also known as the American Wire Gage (A. W. G.), is largely employed. With these notable exceptions, the gage used by the American Steel and Wire Company and by many other manufacturers of steel wire, is the United States Steel Wire Gage (U. S. Stl. W. G.), or the Steel Wire Gage (Stl. W. G.), and all unidentified gage numbers used in this chapter will refer to this gage. The limits of wire drawing range in size from .001 to 1.25 inch for round wire and from a few thousandths of an inch to two inches for square, hexagon and octagon. In manufacturing, widely different sizes require different methods of handling, and steel wire falls into about three classes with respect to size, which may be designated as common wire, fine wire, and large wire. Common wire, the heavier sizes of which are frequently alluded to as coarse wire, is drawn from the standard No. 5 wire rod, and includes all sizes to No. 20 gage, while fine wire includes No. 20 and all wires finer than No. 20.

Surface Finishes of Wire: By properly regulating the various processes of manufacture, wire of any composition, size or shape may be produced with any one of several surface finishes. The more common of these finishes are usually designated as bright, black, black annealed, bright annealed, liquor finish, coppered, tinned, galvanized, and varnished. The bright finish is produced by dry drawing, liquor finish by wet drawing, the annealed finishes by the action of oxygen on the surface in annealing, while the tinned, galvanized and varnished finishes are obtained by subjecting the wire to a coating process as a final operation. The methods of producing these different finishes will be developed more fully in the descriptions to follow.

Temper of Wire: In the wire industry, temper is a word used in referring to the hardness, stiffness and strength of wire. The temper is affected by the amount of carbon or carbon and phosphorus present in the steel, the amount of cold drawing without annealing, and the heat

treatment given the wire. Thus, increasing the carbon content of the steel or submitting the wire to drawing operations increases the temper, while heat treating may either harden or soften the metal, according to whether it is heated to the hardening range and quenched, or annealed. The strength and hardness of low carbon wire are regulated by drawing and annealing operations. The tempers of such wires are usually expressed as hard, medium hard, bright soft, soft and extra soft. Thus the hard temper is obtained by drawing several times in succession without annealing, medium hard by drawing fewer times or only partly annealing, bright soft by giving the wire one light pass through the die after annealing, and soft and extra soft by annealing after drawing to size. Thus it will be seen that by properly correlating all these factors,—composition, drawing, and heat treatment,—the physical properties of steel wire may be varied over a wide range, and wire with any degree of hardness and strength, toughness, ductility, or softness of which the metal is capable can be produced. As an illustration of the possibilities in varying these properties, there may be cited the strength of steel wires, which are regularly made with tensile strengths varying from 50,000 to 400,000 pounds per square inch. It must be remembered, however, that, with but one exception, whatever is done to strengthen the metal will decrease its ductility, and vice versa. The exception refers to the special heat treating process known as patenting, which may, under certain conditions, increase both the strength and ductility of the wire.

SECTION III.

ROLLING THE WIRE ROD.

The Wire Rod: The slender rods or bars of metal from which wire is drawn is known as wire rod, and, as already indicated, all steel wire rod is now produced by hot rolling. It may be made in various shapes and sizes, but for common wires and fine wires, i. e., No. 8 and finer, No. 5 round rod (diam., .207 in.) may be considered as the standard. For large wires the rod will, of course, be somewhat larger than the wire to be made from it, while for other special purposes it may be rolled to the smallest diameter practicable for the rolling mill, which is No. 8 (.162 in.). As the rod comes from the rolling mill, it is wound into coils. These coils are, usually, about thirty inches in diameter inside and weigh from 150 to 300 pounds each. Each coil represents the rod made from a single billet, and its weight, therefore, is determined by the weight of the billet used. While the wire rod represents a finished product of the rolling mills, it constitutes the raw material used in the wire mill and should be considered as the first step in the making of wire, for upon the kind and quality of the rod depends largely the kind and quality or grade of

wire drawn from it, and physical defects in the rod will either cause failures in drawing or remain as more minute defects in the wire. Again, while some wire mills obtain their rods from outside sources, many mills, especially the larger plants, roll their own rods, in which case the rod mills form but a department of the wire mill.

Types of Rod Mills: After it has been made according to specifications, the steel for wire is cast into ingots and rolled on the blooming mill in the usual manner. In some cases the blooming mill is succeeded by a billet mill, and the blooms are rolled into billets 1¾ inches square or less in size. More frequently the product of the blooming mill is a 4- x 4-inch billet, which is cut into lengths to give the weight desired, allowed to cool, inspected, reheated, and then rolled directly into rods. As pointed out in the first section of this chapter, the demand for wire in exceedingly long lengths and in large quantities has led to the development of special mills for rolling the rods. These mills are of four different types, known as: (1) The Morgan, or continuous rod mill. (2) The Garrett, or looping rod mill. (3) The Combination, or continuous and Single Belgian, rod mill, and (4) The double Belgian rod mill. Of these the first two employ fundamentally different principles of rolling, or to be more exact, of roll arrangement, hence will be described somewhat in detail.

The Continuous Rod Mill represents a development which in this country began about 1870. At that time the mill most generally employed for rolling rods was the single train Belgian, or looping, mill. This mill, while it represented a great improvement over the single stand three-high mill, was comparatively inefficient and was limited as to the length of rod it could roll. Since all the rolls were run at the same speed, the billets could be roughed down much faster than the rod could be finished, and, owing to the loops formed and the length of time required for the piece to pass through the finishing rolls, the rod would become too cold to finish, if its length exceeded certain limits. In 1869, however, the Washburn and Moen Manufacturing Company erected at their Grove Street Works, Worcester, Mass., an entirely new type of mill, which had been patented in 1862 by George Bedson of Manchester, England. This mill consisted of a number of pairs of horizontal rolls and an equal number of vertical rolls arranged in a series so that the first, third and succeeding stands of odd number were horizontal, while the second, fourth, and other stands of even number were vertical. This arrangement of the rolls made the draft in any stand at right angles to that in the succeeding stand, and overcame the necessity of giving the piece a quarter turn between passes, as in the looping mill. Then, by placing the stands as close together as possible, he was able to drive the mill through two long shafts, on each of which was mounted a system of gears, whereby the rolls of each stand beyond the first was made to revolve at a rate definitely faster than the

stand preceding. This system of driving was to regulate the speed of the different stands so that the peripheral speed of the rolls in each would be the same, or nearly the same, as the linear speed of the bar, which increases after each pass due to the elongation. In this way the looping of the rod between passes was avoided, and a billet once started in the first stand was rapidly carried through the mill in a straight line, being thus rolled into a rod in one continuous operation. This mill met all expectations as to speed and length of rods rolled, but its output was restricted at first, because the rods could not be coiled and got out of the way as rapidly as the mill could produce them. But C. H. Morgan, who was then general manager for Washburn and Moen, soon overcame this difficulty by devising a power traction reel for coiling the rods. This was the beginning of the development of the automatic reels, which will be described later.

The Morgan Mill: While the Bedson mill represented a great advance in rod rolling, it possessed certain mechanical features which were objectionable. Its chief faults were found to be due to the vertical rolls. They were not easily kept in adjustment, and the shaft and gears for driving them were all beneath the mill floor. The scale and water from the rolls fell upon these gears and bearings and caused excessive wear, which, combined with the difficulty of getting to them under the floor, made them a source of much trouble. After a few years experience with the Bedson Mill, therefore, Morgan and his associates developed the twisting guide, by means of which the vertical rolls could be eliminated and horizontal rolls substituted for them. This was a closed delivering guide in which the grooves were cut in a spiral, so that with this guide properly mounted after any pass the piece was forced through it and twisted a quarter turn before it entered the next pass. Besides overcoming most of the disadvantages of the Bedson Mill, this Morgan plan presented the additional advantage of more than one rolling line, that is, of rolling two or more rods side by side at the same time and on the one set of rolls. This plan of increasing the capacity of the mill, however, increases the difficulty of keeping such mills in adjustment, and was not taken advantage of until some years after the erection of Morgan's first mill. Even with a single rolling line, the development of the mill to a practical basis of operation presented some difficult problems. It is evident that such a mill requires very fine adjustment of the draft, roll diameter, and speed of rotation, for these factors are brought into close relation. The proper relations of all these factors can be determined by mathematical calculation, but as the draft fixed by the grooves in the rolls is affected by the adjustment of the rolls, the temperature of the bar and the composition of the steel, and changes with the wearing of the grooves and bearings, much difficulty was at first experienced in getting the mill adjusted so that the piece would not loop or jam between the different stands of rolls. This difficulty was finally solved by increasing the speed of each stand of rolls enough to

keep the rod under slight tension at all times, and by making the bottom as well as the top roll adjustable, as explained under the heading of continuous billet mills.

Arrangement of Modern Continuous Rod Mills: Since the time of Morgan's first mill, various improvements have been made, not so much in the mill itself as in the auxiliary equipment. These improvements have made it possible to produce a more nearly perfect rod and in greater and greater tonnages. What these tonnages may amount to can be indicated from the delivery speed of the finishing rolls, which in modern continuous mills rolling No. 5 rod is approximately 3200 feet per minute. The actual output of a mill depends upon conditions and the number of rolling lines, which is ordinarily one or two. While mills with three and four rolling lines have been built, it has been found impracticable to roll more than two lines, or strands, simultaneously. With three or four lines the rolls, especially the roughing rolls, have to be increased in length to the point where they are seriously weakened, and it is difficult to keep all the passes on so many lines in proper adjustment. Short rolls are much more rigid than long rolls and are to be preferred on that account, because "springing" of the rolls causes the grooves to "open up" with consequent variation of the section. Furthermore, with more than two lines, the mill takes billets so rapidly that it becomes very difficult to heat them uniformly in a single continuous furnace. The number of stands of rolls in a mill and, to a considerable extent, the general layout of the mill, depends upon the size of billet it is desired to use. As previously pointed out, these are of two or three standard sizes, namely, the small billet, 1¾ or 1½ inches square, and the large, or 4 x 4-inch, billet.

Layouts for Rolling Small Billets: From the standpoint of general efficiency, accuracy and uniformity in size of the product, continuous rod mills are designed, preferably, to roll billets from 1½ to 1¾ inches square and 30 to 38 feet in length. This length just fits the standard rail road freight car, while the section is about the largest that can be rolled satisfactorily without a reheating or increasing the speed of the mill beyond the limits of safety and practicability. To work these sections into No. 5 rod without unduly increasing the danger of developing rolling defects requires from 16 to 18 passes. For straight continuous rolling, that is, where the rolls are all in the same straight line, these passes are split into two groups, known as the roughing and the finishing sets. The roughing set consists of 6 or 8 stands of rolls, the first of which is set as near to the discharge door of the heating furnace as possible, usually within 2 feet. Since the furnace is of the continuous side-discharge type, this arrangement makes it possible, without removing the billet entirely from the furnace to push one end into the rolls, which then withdraw it no faster than it is being rolled. Immediately following the last roughing stand is placed a flying shear, which permits the cropping of bad ends before

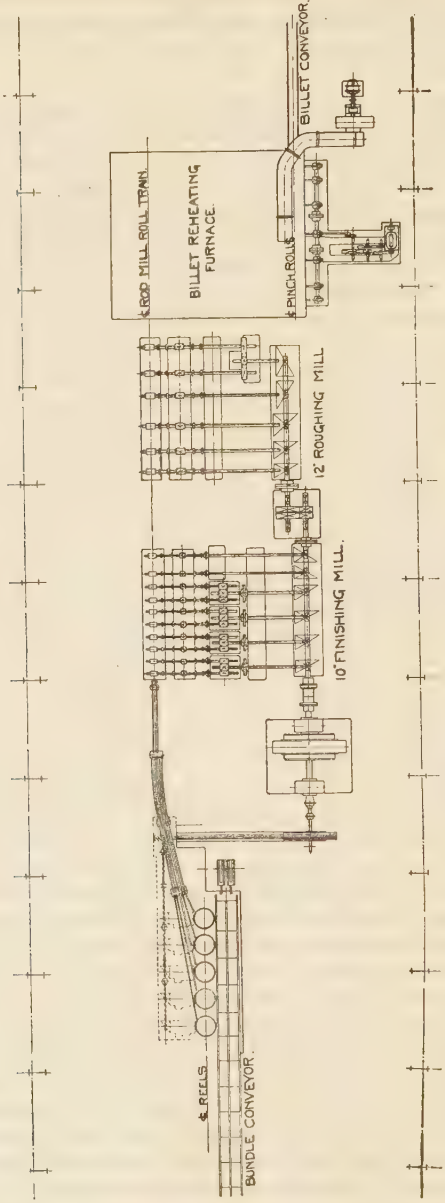


Fig. 229. Plan and Layout of Continuous Rod Mill for 1½-Inch Billets.

the billet enters the high-speed finishing sets. To provide space for these and also for a little slack between the two groups of rolls, so as to make it easier for the roller to keep the mill in proper adjustment, the first stand in the second group is placed about 20 feet from the last roughing stand. The second or finishing group of rolls always contains 10 stands, the first 8 or 9 of which are known as the intermediates and the last as the finishing. Following the finishing stand, tube-like pipe guides are provided for conducting the rod to the reeling machines which are located some 50 to 100 feet beyond and usually number one more than twice the number of rolling lines, or strands. The chief advantages in this arrangement lie in its compactness, which aids in maintaining uniformity of rolling temperature and provides for a choice of different methods of driving. The control of temperature possible is evident from the fact that at the time the forward end of the rod reaches the reelers, two-thirds or more of the billet is still in the furnace. For driving the mill two motors, one for each group of rolls, may be used, but most mills of this type are driven through two shafts connected by gears by a single motor or steam engine.

The Looping Continuous Mill: To provide greater flexibility and make it easier to keep the mill adjusted, the finishing group of rolls in some recent installations of continuous rod mills has been also split up into three smaller groups of 4, 2 and 4 stands each. These smaller groups are so arranged that the 2-stand group is both preceded and followed by 180-degree loops. The roughing rolls and the first four intermediates are in the same straight line, and driven in the usual way by a single motor, while the next two groups, driven by another motor, stand in two separate lines parallel to the first line, with the 2-stand group a little in advance of the finishing stands. Since the roll speeds are adjusted to the elongation of the piece being rolled, the loops, once formed, increase very little in size, and cooling of the rod through this exposure is very slight and uniform for each unit of its length. Also, this placing permits the rolling tension on the rod to be reduced to a minimum, which tension is responsible for most of those rolling defects characteristic of rods rolled on continuous mills.

Layouts for Rolling 4 x 4-Inch Billets: Although the continuous mill is best adapted to roll the small long billet, local conditions frequently make it desirable or necessary to start with a larger size of billet. To meet such conditions, many continuous mills have been designed to use 4 x 4 billets. In designing these mills, the engineers have developed two plans. In one of these an additional group of 6 or 8 roughing or breaking down rolls are provided, and the rod is rolled directly from the billet, as in the straight continuous plan for small billets. The plan has some drawbacks, the chief of which may be noted as follows: If all the rolls are speeded to correspond to the elongation of the bar, the speed of the first roughing group is very slow. Even with the finishing roll revolving at the rate of 1200 r. p. m., which may be considered as about the maximum

rate for safety, the speed of the first roughing rolls would be, with a roll diameter of 14 inches, close to 2 r. p. m. The long time the piece is thus kept in contact with the cold rolls results in cooling it to a point where it becomes difficult to finish. If the first roughing group is speeded up, then the piece must lie waiting before the first intermediates and is cooled even faster and more unevenly than in the former instance. In some cases a solution to this difficulty has been sought by placing a heat retainer, a long narrow brick chamber heated by gas, between the roughing and intermediate groups. By passing the billet through this chamber slowly some of the heat lost in the previous rolling may be restored before it enters the intermediate sets of rolls. But the best plan involves the use of a reheating furnace between these two groups of rolls. In this plan, which in effect is equivalent to placing a billet mill before the usual straight continuous rod mill, the first group of rolls, consisting of 8 stands driven by a separate motor or engine, breaks the 4 x 4 x 72-inch billet, for example, down to a 1¾ x 1¾-inch billet about 30 feet long or to a 1½ x 1½-inch billet about 40 feet long. This long billet is immediately charged into the continuous reheating furnace, where the rolling temperature is fully restored before it is passed into the intermediate group of rolls, which usually consists of 6 stands. From this point the arrangement of the mill does not differ materially from the straight continuous plan already described.

Operation of Continuous Mills: With the mill properly designed and erected, its efficient operation depends largely upon the skill of the operating crews, headed by the roll turner and roller. For best results the roll diameters for the different stands must be carefully selected and maintained in proper proportions; the roll passes, especially for the finishing group of rolls, must be skillfully adjusted and accurately turned; the rolls and guides must be carefully set in the housings; and thereafter the draft must be regulated through the mill screws to suit the conditions. The uniform heating of the billet is also a matter of importance, as is seen from the following facts: Under a given pressure, a hot bar or rod will elongate more than a colder one. Translated into operating terms, this statement means that if the mill is adjusted to roll the colder rod properly, the hotter rod will buckle between passes and cause cobbles. The mill must, therefore, be adjusted to the hottest bars, and if the draft on the different passes is regulated to keep this bar under slight tension the same adjustment will produce a pull of considerable force on the colder bars. This pull is the cause of the longer "finny" ends which are characteristic of rods rolled on straight continuous mills, and it also produces a difference in section between the ends and the middle of the rod, causing it to exhibit a tendency toward flatness in the middle. This matter is especially important in the case of mills rolling more than one line, or strand, at a time. In such a mill, any adjustment of the screws to correct a fault in one pass affects the draft on the corresponding pass of the other strand

also, and it is practically impossible to overcome any variation in temperature of the two strands through adjustment of the rolls only.

The Garrett Mill: Up to 1882 the continuous rod mill had no competitor as to speed, length of the rod, and tonnage produced. On the Belgian, or looping mill, which was the only other type of mill used for rolling rods, the longest lengths that could be rolled would not exceed 300 feet, the heaviest coils weighed less than 50 pounds, and the tonnage produced daily would not, in case of small rod, under .2 in. diameter, much exceed 20 tons. On such mills the best rolling practice of that day for steel involved the rolling of the ingots to 4 x 4-inch blooms, which were cut into lengths convenient for hand rolling and allowed to cool. These blooms, or billets, were then reheated and rolled on a three-high billet mill to a 2-inch square or its equivalent in rectangular section. These small billets were again sheared into lengths to give the weights required and allowed to cool, when they were reheated and rolled into rods on the looping mill. In endeavoring to overcome the advantages enjoyed by the owners of the continuous rod mill, William Garrett, who was then superintendent of the plant of the Cleveland Rolling Mill Co., conceived a plan whereby the looping mill could be modified to roll number 5 rod in long lengths and direct from 4 x 4-inch billets without reheating. In formulating this plan, he reasoned that, since a large section loses heat less rapidly than a small one, the 4 x 4-inch billet could be rolled in the roughing mill to a size suitable for the rod mill in so short a time that it would still retain enough heat to be finished if it were not exposed so long in the looping mill. So he combined the three-high billet mill with the rod mill, and split up the latter into three groups or trains of rolls, which he arranged in echelon and drove at progressively increasing rates, so as to rough at low and finish at high speeds. By this arrangement the speed of the finishing trains could be adjusted to the elongation of the rod, so that not only could a given length be rolled in a shorter period of time, but the size of the loops could be controlled and their length reduced. Garrett erected his first mill in 1882, and at once he was able not only to roll rod in much longer lengths, but also to double, and more than double, the output of the older looping mills.

Accessories to Garrett's Mill: After the erection of his first mill, Garrett was able to add certain improvements from time to time, until finally the production on his mills surpassed in tonnage that made by the continuous mills, though the latter mills have kept in the lead as to the length of rods rolled. One of the most important of these improvements was his use of repeaters. As pointed out in connection with merchant mills, these are semi-circular trough-like guides placed so as to guide the end of the piece from one pass to the next. As the repeaters are open at the top, a loop once formed is free to rise out of the trough, and enlarge to correspond to the elongation, or otherwise adjust itself

to any difference in the speeds of the two passes. A looping mill fully equipped with repeaters is practically as automatic as a continuous mill. In the case of looping rod mills, however, they do not work equally well on both sides of a mill. In these mills, the passes from the first few roughing stands to the finishing are alternately oval and square, the squares coming out on one side of the mill and the ovals on the other. On entering the square passes, the ovals must be turned on edge, and the use of guides for doing this work generally results in the production of much scrap, due to their frequent failures to edge the ovals properly. In modern Garrett mills, therefore, catchers are generally employed on the oval side, while repeaters are used only on the square side. The net result of this improvement then, has been to reduce the labor force by about one-half.

Number of Strands: Another improvement introduced by Garrett, who was the first to employ the scheme, was the practice of finishing more than one rod at a time. Due to the shortness of the billet, the roughing train is able to break down the billets much faster than the finishing train can roll the rod in a single strand, even when the latter is speeded up to 550 r. p. m., which is the maximum speed at which it is practicable to run this train. Since the rod makes only one pass in the finishing and most of the intermediate stands, there is a great amount of roll space unused in rolling a single strand. By adopting power reels, and reeling each strand on independent reels, Garrett found no difficulty in finishing two strands at once in the same trains and thus doubling the output of the mill. In modern mills, four, and even six, strands may be rolled simultaneously. The number of strands rolling in a looping mill has considerable effect upon the forming of the rod, and it is considered good practice to keep the mill as full as possible.

Floors: Another characteristic of looping rod mills is the sloping floors, which, though a simple device, play an important part in their operation. Since it is necessary to run the rolls in each finishing train at the same rotative speed, and it is not practicable to take up all the elongation of the piece, or equalize the rolling time of the different passes, by using rolls of different diameters, it is necessary to allow the loops, which are formed after catching or repeating, to grow upon loop floors. If these floors are level the frictional resistance soon becomes so great that it stops the forward motion of the loop, when the rod will pile up and become hopelessly twisted. In the old days, boys were employed to draw the loops back with hooks or tongs, but in Garrett mills this frictional resistance is overcome by laying the looping floors at an incline, sloping from the rolls, except on the oval side where a narrow level space is left to provide standing room for the catchers. When more than one strand is being rolled, as in all modern mills, these floors must be provided with guiding channels and other facilities to prevent the different loops from becoming entangled.

Layout of Garrett Mills: The arrangement of the roll-trains in

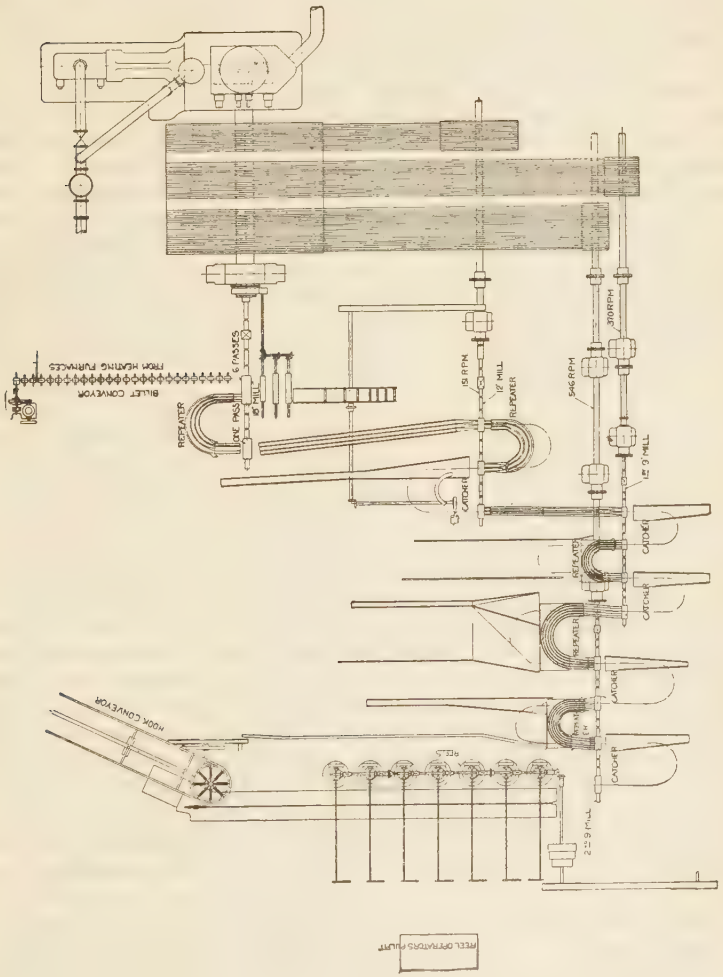


Fig. 230. General Layout of Garrett Rod Mill.

modern looping mills has been subjected to considerable variation. As originally planned by Garrett, the three-high billet mill was placed near the heating furnaces, which are now mainly of the continuous end-discharging type with floors sloping downward from the charging end. Two or more of these furnaces may be used to heat the billets, which are conveyed to the mill by roll tables. Following the billet mill at a distance great enough to permit the piece from the last pass to clear the rolls is the roughing mill, which, in modern mills, may be a looping train of three stands or two or more stands arranged in tandem. Then come, with their looping floors sloping in opposite directions from the narrow level standing, the intermediate and finishing rolls, arranged, usually, in two trains of four or five stands each, lying end to end along two parallel lines in close proximity to each other, and so placed that the first intermediate pass is in line with the last roughing pass and far enough away to give proper clearance for the piece. In some mills especially designed to roll small rods, the finishing and last intermediate stands are coupled together in a third and separate train, which is driven at the highest speeds practicable, to reduce the size of the loops and make it possible to finish the rod at a higher temperature.

Combination Mills: In roughing down the 4 x 4-inch billets on the three-high mill, considerable time is consumed in making the necessary 5 to 7 passes back and forth through the rolls. Not only does this delay tend to cool the steel somewhat, but these operations require some heavy hand labor. To overcome these disadvantages as far as possible, some looping mills make use of a group of continuous rolls for roughing purposes. This group usually consists of eight stands, and displaces not only the billet mill but the roughing train as well. With such a group, the work of roughing can be done much faster than the looping trains can dispose of the material even when four strands are rolled at once. Consequently, one continuous roughing mill is used to feed two looping finishing mills, one of which is placed on the right and the other on the left side of the roughing mill. By locating these finishing trains at a suitable distance beyond the roughing mill, the sections from the last roughing stand are carried forward or looped into the first intermediate pass by means of guides similar to the repeaters previously described. This type of mill is sometimes referred to as the Garrett semi-continuous mill.

The Double Belgian Mill, which is also designated by the name of Boecker's wire mill, represents another attempt to combine the continuous and looping methods of rolling, in this case, to the finishing mill. It consists, usually, of 7 or 9 stands of rolls, 6 or 8 of which are arranged in two parallel lines or trains of 3 or 4 stands each, so that the corresponding stands in each line are opposite each other, thus forming 3 or 4 continuous groups of two stands each. The mill is driven from a central shaft lying between the two parallel lines of stands, and from this shaft the power is

transmitted to the rolls through three sets of gears. In this way the speed and direction of rotation of the various rolls is so regulated that a rod, in passing through the mill, can be looped by catchers or repeaters from one continuous set to another, and from the last continuous set into the single finishing stand, which is two-high. A mill of this design offers some of the advantages of both the looping and continuous types, but also possesses some of the limitations of both. Thus, while it is capable of producing rods that are exceptionally uniform in section, the complicated system of shafting and gearing makes its upkeep expensive and tends to offset its advantages.

Continuous and Looping Mills Compared: A just comparison of the continuous mill and the looping mill is difficult to make. Local conditions and a great number of other factors must all be considered. For example, there is the matter of raw material. The small billet of full standard length, i. e., 30 to 38 feet, cannot be rolled on a looping mill because of the long exposure on the looping floor, which cools it below the temperature for hot finishing. On the other hand, the continuous mill is particularly suited to rolling these long billets, and, when combined with the special heating furnace previously referred to, presents a layout by which the rolling can be done at higher and more uniform temperatures, which saves power and minimizes the variation in section of the rod from end to end.

As already pointed out the large, or 4 x 4-inch, billet may be rolled on the continuous, the Garrett, or the combination mill. Mills of the Garrett type with looping trains for all except the first roughing, or billet mill, are limited to a billet weight of about 175 pounds, because, with a larger billet, the last end of the rod becomes so cold that excessive power is required to roll it, and the variation in size of the rod from end to end is too great to be tolerated. Continuous mills and combination mills can roll, without a second reheating, 4 x 4-inch billets weighing up to 220 pounds. On billets of these weights, the continuous mill requires less power and fewer men to operate it than mills which are chiefly of the looping type, but the repairs on the continuous mill are somewhat more numerous and costly than on the looping mills, due to the higher roll speeds and the difference in guides and type of drive. By providing a second reheating furnace for restoring the temperature of the partly rolled 4 x 4-inch billet, continuous mills can roll rod, either from large or small billets, in single lengths weighing up to 300 pounds. Up to this limit, at least, the heavier the rod bundle the better, on account of the longer length of the wire that can be drawn from it in one piece, which reduces the labor required and the scrap produced in the drawing and finishing operations. Offsetting this advantage, however, is the fact that the straight continuous mill, itself, generally makes a higher percentage of scrap than looping mills; also, the rod rolled on the continuous mill, being

finished at a higher temperature than the looping mill rod, has a heavier coating of scale, which causes a greater direct metal loss and requires a greater quantity of acid for pickling, or cleaning, precedent to the wire drawing operation.

As to other differences made in the product by these two methods of rolling, these are of such a character as to leave little from which to choose. The tendency exhibited by the continuous mill rod toward flatness in the middle is offset by the variation in section from end to end of the looping mill rod when rolled in long lengths. Since the continuous mill cools the rod during the rolling less than the looping mill and uses no hand labor for catching, it permits, without adding very much to the labor costs, the use of a greater number of roll stands and passes. This great number of passes makes it possible to use better shaped passes with smaller reductions from pass to pass, and thus avoid overfills, which frequently cause surface defects in the rod,—defects that are of very serious character in many wire products.

A Comparison of Actual Costs of rolling rods by these two methods is difficult to make. To do justice to both, such a comparison cannot be based merely upon the rolling of rods from billets, for the cost of rolling the billets from ingots is also involved. In the best designed plants employing the two systems of rolling, it is probable that the difference in cost of production is very small. On this assumption, the opinion of the majority is that the advantages of continuous rolling outweigh the disadvantages, and the most recent installations have been of the continuous type.

Rolls for Rod Mills: As to size, the rolls used for rolling rods are subject to considerable variation according to the type of mill and the purpose for which they are used. Thus, in Garrett mills the rolls are long, and vary in diameter from 16 or 18 inches for the first roughing rolls to 9 or 12 inches for the intermediate and finishing rolls, while in continuous mills using 4 x 4-inch billets they vary from about 14 inches for the roughers to about 10 inches for the finishing groups. The roughing rolls may all be of cast steel or some of cast steel and some of adamite, but the intermediate and finishing rolls are all made of cast iron and are cast in chills to produce a harder and more durable wearing surface. As to the roll passes, these are simple in form but of a design to give the necessary reduction without developing defects in the material. In Garrett mills and continuous mills using 4 x 4-inch billets, the first few roughing passes are rectangular, or box passes, but in all other rolls except the finishing the passes for round wire are arranged to give alternately squares and ovals. For round wire the last oval feeds the finishing pass, which, of course, must be circular. To reduce the number of roll changes otherwise necessary, a number of duplicate grooves are cut in each set or pair of rolls, so that when one set of grooves becomes defective or too badly

worn a new set can be made available for use merely by resetting the guides. When all the grooves in a set of rolls have thus been used, they must be replaced by a new set while the worn rolls are being redressed, so that duplicate rolls as well as duplicate grooves are required.

In Designing the Passes, the matter of chief concern is the proper regulation of the draft in each pass. The highest drafts are made in the roughers, where the reduction in any one pass may be as high as 45 per cent., though a limit of 35 per cent. represents better practice. In the intermediate sets of rolls, a maximum draft of about 30 per cent. may be attained in the first passes, but as the rod approaches the finishing pass the amount of the reduction permissible gradually diminishes, until in the final pass it is well under 15 per cent. Within the limits mentioned, the drafts will be determined largely by the number of passes provided by the mill, which in turn will depend upon the type of mill, the size of billet used, and also the size of rod to be rolled. For rolling 4 x 4-inch billets to No. 5 rod, Garrett mills usually provide from 18 to 20 passes; some continuous mills use 21 passes, while others provided with an intermediate reheating furnace may use as high as 24; and combination and double Belgian mills may use 18 to 24 passes. Nearly all the mills are so arranged that the size of the finished rod can be varied, that is, made coarser than No. 5, either by "opening up the mill," thereby producing larger sections in each pass, or by omitting the use of some of the stands immediately preceding the last. In the latter case the finishing is done on one of the stands used as an intermediate when rolling No. 5 rod.

Housings and Guides: The construction of housings, with their mechanism for making necessary adjustments of rolls and guides, differs in the different mills, but is the same in principle as described elsewhere in this book for corresponding types of billet and merchant mills. The setting and adjustment of the rolls and of the receiving and delivery guides require a great deal of experience, and, upon the efficiency of the man making these adjustments, depends in great measure the quality of the rolled rod as well as the tonnage of the mill.

Rod Reels: The daily output of rod mills in use today varies from 450 to 750 tons, which tonnages, translated into linear units of No. 5 rod, are equivalent to about 1500 and 2500 miles, respectively. From this statement it is evident that this enormous output would have been impossible without adequate reeling facilities. As previously pointed out, this need caused the early adoption of automatic reels, the first practical development of which was introduced about 1880. The rod reels now in use are mainly of two types, known as the pouring reel and the pipe reel. The pouring reel consists essentially of a horizontal steel disc or pan mounted upon a vertical shaft so that it may be revolved at a speed corresponding to the delivery speed of the rod. Near the circumference of this pan are two circular and concentric rows of pins, or spokes as they are often called.

Into the annular space bounded by these spokes the rod pours from the curved end of a pipe which conducts it from the finishing rolls, and since the rotative speed of the reel is adjusted to the linear speed of the rod, the latter is laid in a neat coil within this space, a single ring of the coil being formed at each revolution of the machine. In the pipe reel, the receptacle is stationary, while the end of the delivery pipe, itself, is made to revolve in a circle, thus laying the rod within the annular space provided by a motion similar to that in coiling a long rope by hand, so that the rod is given a twist at each revolution of the pipe, or as each ring of the coil is formed. The pipe reel, therefore, can be used only with small round sections, and in modern mills most of the installations are of the pouring type. In both types the diameters of the coils are determined by the relation between the delivery speed of the rod and the rotative speed of the reel, for the periphery speed of the coil forming must equal its delivery speed. As these two factors cannot always be kept in exactly the same relation, the diameters of the coils vary somewhat. In all cases the reels are designed to raise the coil or lower the spokes, and deliver the product upon a rod conveyor, which carries each coil to some designated point where it may be disposed of as desired. In case of wire manufacturers who roll their own rods, the rod mill is located very near the wire mill, and the coils are carried by the conveyor directly into the cleaning or heat treating departments of the latter. Most wire mills, whether they roll their own rods or not, will be provided with covered yards where rods of various kinds of stock may be stored for use as required.

Defects in Rods: To produce a satisfactory rod requires that proper care be exercised in every department concerned with its preparation. To begin with, the steel must be properly made and its composition should be uniform and as near that desired as possible; also, it is essential that the ingot be properly cast and rolled at a suitable temperature, and that the billet be free from pipe, seams, and slivers. Even with perfect billets, considerable care and skill are required to produce satisfactory rods. Assuming that the rod mill, itself, has been properly designed and speeded and equipped with all the necessary accessories, unsatisfactory rod may still be produced by improper heating, by the use of improperly designed ragging on the roughing rolls, by improperly adjusting the rolls and guides, or by using the grooves too long. In order to finish the rod correctly, every pass in the mill should be made to produce, as near as possible, the section it was originally designed to produce, and to bring about this result all the passes must be kept full but none may be allowed to overfill. Great emphasis is to be laid upon all these features of operation, because, from the point of view of the wire mill it is most essential that the rod be uniform in composition, and also in section, that it be close to the size and shape required, and that it be free from such surface defects as slivers, seams, and fins. These defects, as well as the composition, are matters

of importance to both the consumer and the wire mill, for none of the subsequent wire-drawing operations or finishing processes will eliminate them or reduce their capacity to do harm in the final product.

SECTION IV.

GENERAL OUTLINE OF WIRE-DRAWING PROCESSES.

Plan of Study: Unlike the rolling of the rod, which is a fairly well standardized process, the working of the rods into wire is subject to much variation. Aside from differences in the methods of manufacturing the steel, the only differences existing in the rods are those of size, shape, and composition. For common round wires and fine wire, these differences in the rod disappear almost entirely, because all these wires are produced from low carbon stock rolled into the standard No. 5 rod. True, the composition of these rods may be varied somewhat, but from rods of the same composition, or even from the same rod, wires differing not only in size but also in finish and temper may be produced. In order to secure these differences, different wires must be subjected to different processes, or different procedures. Consequently, no one wire or one kind of wire can be taken as an example to describe the manufacture of all wires, while their great number of varieties makes it inadvisable to attempt to describe the manufacture of each in detail here. However, all these processes may be classified and discussed in a general way, so that the mode of procedure to be followed in producing any given wire can be readily worked out. This plan permits the freest discussion of the principles involved in each process, is the least likely to confuse the general reader, and permits the inclusion within the smallest space the greatest amount of information of most use to those engaged in the industry. This plan, however, presupposes that the reader has a general idea of the principal operations and processes used in wire drawing, or a sort of birds-eye view of the industry, such as might be obtained on a brief tour of all the wire-drawing plants of the country. For the benefit of those who lack such knowledge, a brief sketch of the history of wire from rod to finished product will be given.

Preparing the Rod for Drawing: In order to prepare the rod for drawing, it is first given a number of preliminary treatments. These treatments vary in number and character according to the kind or grade of steel in the rod, the amount of drawing to be done, and the kind of finish desired on the wire. In the case of certain high carbon wires, for example, the rods will first be heat treated to give them a uniform structure and develop their drawing properties. In the case of low carbon rods this treatment is not necessary. With this exception the coils of rods are delivered from the mills or from storage direct to the cleaning house.

Here, the first operation is that of cleaning, which consists in lowering the coils into vats containing hot dilute sulphuric acid for 15 to 30 minutes. The action of the acid loosens the scale and frees the rod of all rust and other dirt, leaving it perfectly clean. Upon being withdrawn from the acid vats the coils are washed with fresh water, and then coated to protect the surface of the rod from the air and facilitate the drawing of it into wire. This coating may be done in different ways, and is varied according to the kind of wire being drawn, but for most wires the procedure is about as follows: Upon their being thoroughly rinsed, the coils of rods may be placed on a rack and kept moist with fine sprays of water until a brownish rust appears. This process is called sulling, and as it darkens the color of the rod, it is not used for bright wires. After rinsing or rinsing and sulling, then, the coils are dipped into vats containing hot milk of lime, which adheres to the surface, completely covering the rod with a thin coat of white wash. From the lime vats, the coils of rods are loaded upon metal buggies and passed to the dry house, where the buggies are pushed directly into the bakers. These bakers are long, narrow brick chambers, kept at a temperature of 250° to 400° F. Here the rods are allowed to remain for several hours, for, besides drying the coating, the baking has another function, which will be explained later.

Drawing the Rod: With the rod coils in proper condition to be drawn into the kind of wire desired, they are trucked to the wire-drawing department. Here, the coils are placed separately upon a reel, drum, or other suitable receptacle before the wire-drawing machine, which is technically known as a wire-drawing frame. This frame, in the type most generally used for drawing rods, supports a single die and the power driven block for drawing the rod through the die, also a draw bar for drawing the first few feet of the rod, and any other devices necessary for the proper handling of the material. With one of these devices one end of the rod is now pointed, or tapered, so that it may be threaded through the die hole, which is somewhat smaller than the rod in section. Next the die holder, on the entering side of the die, is filled with a specially prepared grease, or some other suitable lubricant, so that in passing through the die the rod must first pass through the lubricant. The pointed end of the rod is now inserted through the proper die hole, where it is grasped by tongs attached to the draw-bar, and drawn through far enough to be attached to the draw block. When this block is started revolving, it coils the wire about itself and thus continuously draws the rod through the die, thereby bringing about a fixed decrease in its sectional area and a proportional increase in its length.

Draft, Drawing and Process Wire: The amount of the reduction in the sectional area, as in the case of rolling, is expressed in per cent. of the original area and is known as the draft, while the operation itself, is called drawing. In general the draft on the rod varies from 10 to 45

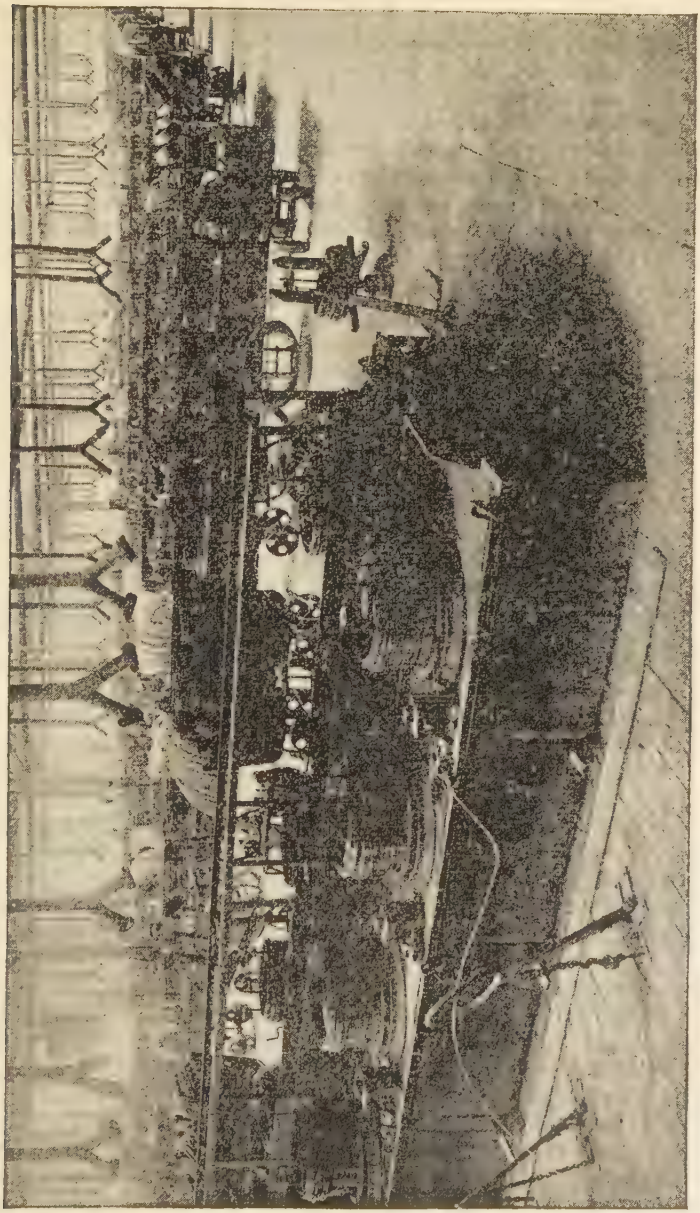


FIG. 231. A Wire Drawing Room. Showing arrangement of draw benches or frames, and method of handling wire during the drawing.

per cent., according to the kind of wire to be made. As soon as a rod has been given a draft, it is thereafter designated as a wire, though many more drafts and various other treatments may be necessary to work it into wire of the size, finish and temper desired. In wire drawing plants, any wire, which, following the initial drawing from the rod, is to receive further work or treatment before it is finished is designated as process wire. After the first draft from the rod, process wire, as already pointed out, may be finished in various ways, and it becomes necessary at this point to explain that there are different methods of drawing and also different processes for drawing wire.

Dry and Wet Drawing: The processes for drawing wire are two in number and are designated as dry drawing and wet drawing. Neither of these processes involve any change in the actual operation of drawing, which may remain the same in both; but, in the matter of preparing the wire for drawing, they differ widely. In dry drawing, the wire is cleaned with acid, coated, baked, and drawn dry through a lubricant, by processes analogous to those already described for the drawing of rods. By this method of drawing, the surface finish commercially known as lime bright or bright, is obtained, the wire having the color and luster characteristic of highly polished steel. This finish may not be obtained in all dry-drawing, because the degree of brightness depends upon the coatings and lubricants used and upon the number of drafts given the wire successively. In wet drawing, the wire, after a thorough cleaning, is immersed in a dilute solution of copper or tin sulphate or a mixture of both of these salts, then placed in a vat of fermented liquor made from rye meal and yeast, from which it is drawn wet with the liquor serving as a lubricant. During the time the wire remains in the salt solution, a chemical action takes place which results in the deposition upon the wire of a thin coating of copper or a mixture of copper and tin, depending upon the composition of the solution used. Upon drawing, these coatings impart characteristic colors to the wire, which are known commercially as coppered wire and liquor finish, the latter term designating the brass colored finish obtained from the copper-tin coating. In general, wet drawing gives a cleaner, brighter, and more durable finish than dry-drawing, but is more expensive.

Methods of Drawing: There are two methods of drawing wire, designated as single draft drawing and continuous drawing. As the name indicates, single draft drawing consists in drawing the wire through only one die at a time, in the manner already described for the first draft on rods. If more than one draft is necessary to finish the wire, the coil must be removed from the block, and the wire redrawn through a smaller hole, these operations being repeated for each draft until the wire has been drawn down to the size desired or has become too hard and brittle for further drawing. This is the older of the two methods, and is still the one most generally used. In continuous drawing, a special machine is

used, which consists essentially of a number of dies and properly speeded blocks, or revolving drums, arranged in a series so that each die is followed by a drum. In operating this machine, the wire is wound about each of the intermediate drums a sufficient number of turns to draw it through the preceding die, and is coiled on the last drum as in single draft drawing. In this way a wire may be given several drafts in the one operation, and the work of withdrawing the coil from the block after each draft is eliminated. The method, however, has certain draw-backs that tend to offset this advantage, so that this mode of drawing has not been generally adopted.

Finishing Wire: Following the first draft, the procedure for finishing the wire varies according to the kind of wire, whether low or high carbon; the size of the wire, whether coarse or fine; the finish, whether bright, annealed, coppered or liquor, galvanized or tinned; and the temper, whether soft, hard, or medium, etc. It is impossible in the space allotted this section to give an accurate description of all the processes required to achieve these results in all the different varieties of wire, but a brief sketch to supply a mental picture as a basis for the discussions to follow is here attempted under the following headings.

Finishing Low Carbon Coarse Wires: Under this heading are included all common wires coarser than 18 or 20 gage, nail wire, fence wire, telephone and telegraph wire, and wire used for bolts, screws, etc. As a class this wire may be finished in many different ways. Thus, one draft may be all that is necessary to finish the wire; or after the first draft, the wire may be finished by giving it an additional number of dry drafts, which procedure gives the hard bright wires. If the use to which the wire is to be put requires ductility, softness, or pliability, the wire must be annealed. For maximum softness and ductility the annealing must be the final operation. This process gives the annealed finishes, which vary in color from black through blue and yellow to almost bright, according to the method of annealing used, which in turn will be governed by the requirements. To produce bright soft wire, the wire is drawn almost to size, annealed, cleaned and given a final dry draft to finish. To produce the coppered or the liquor finish, which is very desirable for many purposes, the wire is drawn dry to almost the size required, then cleaned or annealed and cleaned, and sent to the wet drawing department for the final drafts to size.

Drawing Fine Wires: Fine wires, generally, are made of low carbon steel, and for mechanical reasons they must be finished by wet drawing. After they have been drawn dry to about No. 13 or No. 18 gage, according to the size and kind of wire being made, these wires are annealed, cleaned, and drawn dry to about No. 20 gage; then they are coated, or annealed and coated, according to kind of finish desired, and drawn wet to the size desired, or to as small a size as possible without annealing.

The total number of drafts and annealings will depend upon the size and kind of wire, the finest wires requiring a score or more drafts and three or more annealings to finish them.

Drawing High Carbon Wires: The carbon content of the class here designated as high carbon wires varies from .30 to 1.20 per cent. This class includes rope wire, spring wire, spoke wire, brush wire, card wire, safety pin wire, music wire, pile wire, pivot wire, sewing machine needle wire and various other highly specialized products known in the plants as special wires. The methods used for drawing these products are the same in general as those used for the low carbon wires, and may be said to differ from the latter only in details, though these differences are frequently of great importance. As to the heat treatment, high carbon wires in process are generally patented instead of annealed, because this process gives better drafting qualities and a stronger, tougher product than annealing. This is a special process, peculiar to the wire industry, for developing a sorbitic structure, and will be described more in detail later.

Other Finishing Operations: After the wire has been drawn, various other operations may be necessary to prepare it fully for use. Thus some wire is required to be delivered in straight lengths, and as it is drawn in coils, these must be cut into the lengths desired and straightened by an additional operation. Some wire, like market wire and stone wire, is put up in packages or bundles of exact weights, and these require additional operations. Market wire is a term applied to the low carbon wires, usually of soft Bessemer steel, supplied to jobbers in exact weight bundles. The standard weight for these bundles is 100 pounds, but 63-pound bundles are sometimes requested. It includes all finishes and many sizes suitable for many different uses, as, broom wire, fence wire, mattress wire, netting wire, weaving wire, etc. Stone wire is always finer than 16 gage, and is put up in 12-pound coils, 8 inches in diameter, covered with paper and labeled. To preserve the wire from corrosion it must be given some kind of protective coating. This statement applies to wet drawn wire as well as dry drawn, for the copper and brass coatings on the former are very thin and offer little protection to wire exposed to weathering. For temporary protection, the coating may consist of a varnish or paint applied by dipping. But for more lasting protection, the wire must be galvanized or tinned, and to apply these coatings it must be thoroughly cleaned and passed through baths of these metals kept in the molten state. To do this work properly, the wire must be put through series of processes requiring special equipment and expert workmen, hence galvanizing and tinning are done in separate departments. Finally, there are the fabricated wire commodities, many of which, such as nails, bale ties, springs, wire rope, concrete reinforcing, barbed and woven wire fencing, are fabricated by the wire manufacturer. Leaving these products for a future

section, we shall turn to the general discussion which is conveniently divided into six sections, namely, Preparation of Rods and Wire for Drawing, Wire Drawing Equipment, Wire Drawing Processes and Operations, Heat Treatment of Wire, Protective Metallic Coatings for Wire, and Some Fabricated Wire Products.

SECTION V.

PROCESSES AND EQUIPMENT FOR PREPARING RODS AND WIRES FOR DRAWING.

Importance of Cleaning: The hard, black brittle oxide, commonly called scale, which forms on the surface of hot rolled rods and annealed wire, and also the slow-forming red rust which forms on long exposure to the air, must be entirely removed before drawing, as, otherwise, the holes in the dies would be quickly cut out of shape and the surface of the wire would be spoiled. Success in wire-drawing, therefore, depends in a large measure upon the thoroughness with which the cleaning is done.

Method of Cleaning: As already stated, the method generally employed for cleaning the material preparatory to drawing consists in dipping the coils into a vat of hot dilute sulphuric acid. The action by which this acid removes the scale is for the most part mechanical rather than chemical, for ferroso-ferric oxide, Fe_3O_4, which is the chief constituent of the scale, is but slightly soluble in sulphuric acid. The acid, however, is able to penetrate to the metal beneath the scale, where it acts upon the iron, forming iron sulphate, a soluble neutral salt, and liberating a mixture of gases, mainly composed of hydrogen. This action results in loosening and detaching the scale from the surface of the metal, when it sinks to the bottom of the vat where it accumulates and must be removed at frequent intervals. Unlike the black scale, the red rust, which is a hydrated sesquioxide of iron of the general formula XFe_2O_3, YH_2O or a double compound of ferric oxide and ferric hydroxide, $Fe_2O_2 \cdot 2Fe(OH)_3$, is readily soluble in sulphuric acid, and under the conditions of pickling this action results in the formation of iron sulphate, also. This salt remains in solution, and as concentrated acid is added from time to time to replace that neutralized, the solution eventually becomes saturated to such an extent that it is no longer fit for pickling. The exhausted solution is then pumped to a recovery plant and the salt is saved by an evaporation and crystallization process.

Manner of Handling the Material. In order to facilitate the handling of the bundles of rods and the coarser sizes of wire during the cleaning and coating operations, several of them are strung on a device called a yoke. These yokes are of two chief types. One type, in construction,

resembles a large safety pin, one end of the pin being permanently attached to the yoke. In the other type, which is the more common, the yoke and the pin are separate. The yoke represents a long bar with a hole or eye at the center for the attachment of a hook from above, and with a hanger at each end for supporting the ends of the pin from below. In using the device, the yoke, supported from the hook of a crane or other lifting device, is lowered over a number of coils standing on edge adjacent to each other, and the pin, which has been inserted through these coils is adjusted so that its ends rest in the hangers on each end of the yoke. Thus, upon lifting the yoke, the coils hang suspended from the pin. The yokes and pins may be made of either wood or some non-corroding metal, and are of sundry lengths, or sizes, depending upon the size of the vats, which in turn depend upon the number and size of the coils to be handled. The yoke with its pin and load of bundles is known as a pin of rods or a pin of wire, and remains intact as a single unit throughout the entire cleaning and coating processes.

Types of Cranes Used: While there are in use different methods for handling pins of rods and wire, the most adaptable method and the one generally used involves the use of cranes. These cranes are of three different types. The one ordinarily used consists of a strong upright standard, from the upper end of which extends a horizontal arm or boom. This standard is supported in metal bearings at its top and bottom and can be revolved so that the end of the boom will describe a complete circle. The boom must extend at least to the center of the vats which are located at the foot of the standard; hence, in general, these booms vary in length from 10 to 18 feet according to the size of the vats. In dipping the material, the pins of rods or wire are lifted and supported by a steam or hydraulic piston acting through a cable which passes over a sheave at the outer end of the boom. This piston may be anchored either to the boom or to the vertical standard, in which latter case two sheaves, one at each end of the boom, are required. In the second type of crane, commonly known as the grasshopper crane, the boom itself is raised and lowered and no hoisting cable is required. The power for hoisting is applied directly to the boom, by means of a piston actuated by steam, compressed air or hydraulic pressure. The third type is the ordinary electric traveling crane; its use involves a different arrangement of the vats from that used with the other two types, for, in this case, the various vats and the tubs must be placed in a row so that the hoist may pass over them in succession. This crane is used only to a limited extent, one of the other revolving types being generally preferred.

Construction of Vats: The acid vats are generally made of wood, and in form and construction resemble large tubs. As to size, they are made large enough to receive either one or two pins of rods or wire. The one-pin tubs have a capacity of about 500 gallons, and the two-pin tubs, a capacity of 1200 to 1400 gallons. The one-pin tubs are suitable for wire

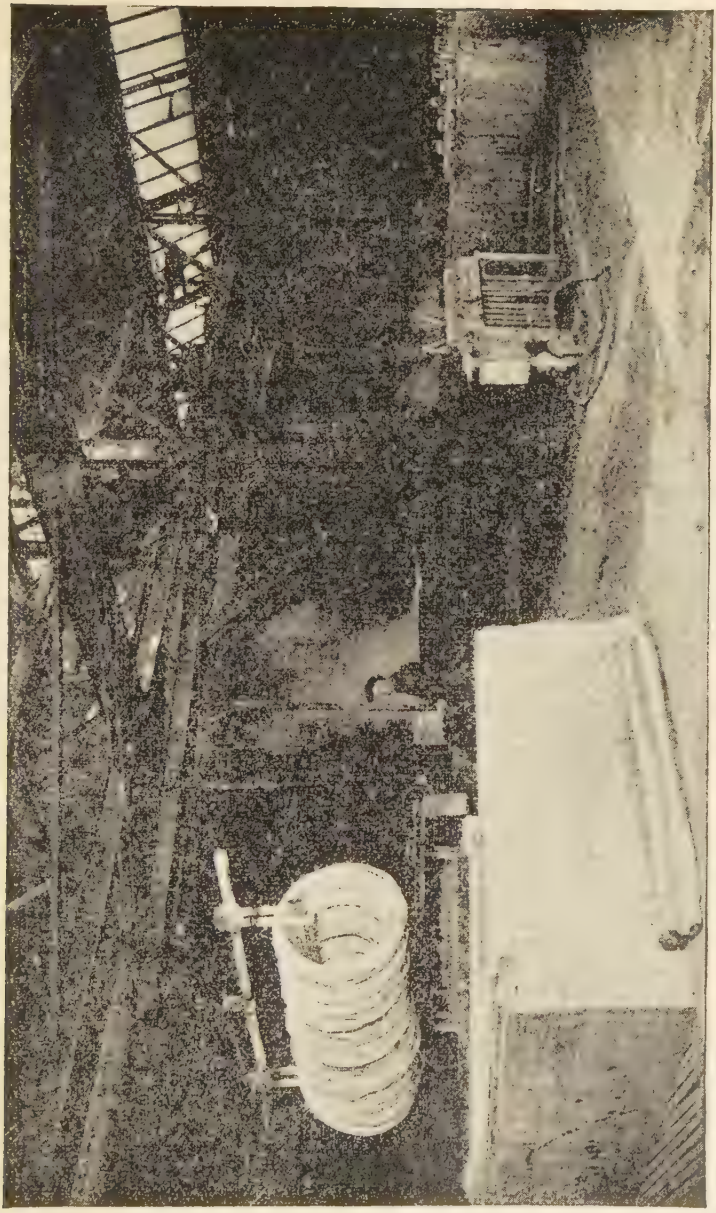


FIG. 232. Cleaning Rods. Showing Pin of Rods about to be Lowered into Pickling Tub.

rather than rods. Since the coils of wire are smaller in diameter than the coils of rods, the tubs for cleaning rods must have a greater depth than those for cleaning wire, only. The acid in the vats is heated by means of live steam, hence each tub is provided with a number of perforated lead pipes which extend from the steam line down the side of the tub and, in some cases, across the bottom. The water vats are also constructed of wood, but are generally rectangular or box-like in shape. They are, therefore, usually referred to as the water boxes. The lime tubs may be of the same size and shape as the acid vats, or they may be of a box construction like the water boxes. These are heated either by steam coils or with live steam, as in the case of the acid vats.

The Arrangement of Vats and Cranes, as already indicated, depends primarily upon the type of crane used. With the stationary revolving cranes two different arrangements are possible. If the material to be cleaned varies considerably in size or kind and if the tonnage is small, it is the practice to arrange the various cleaning and coating tubs and the sulling rack in a circle around a single crane, whereas, if only one kind of material is involved and if the tonnage is large, the cleaning and coating equipments are grouped about two cranes working in conjunction. In the latter case, the first crane, surrounded by from three to five acid vats and a rinse tub of water, is employed for cleaning and rinsing and for placing the rinsed pins on one end of the continuously moving sulling rack, while the second crane, surrounded by from one to three lime tubs, one copper sulphate tub, and one or two acid vats, picks up the pins at the other end of the sulling rack and transfers them to the different vats for recleaning, lime coating or copper coating. All this equipment is contained in a separate room or building, known as the cleaning house, which should be and usually is, located at some place convenient to the wire mill. In this house special provision must be made for the drainage of waste water and acid, and also for the removal of the steam and acid fumes, which otherwise would be very destructive to the building and machinery and harmful to the health of the men as well. As previously stated, the spent acid is pumped from the acid vats to other tanks where it is completely neutralized with scrap, and the iron sulphate later recovered by evaporation. To take care of the drip from the coils after rinsing, the floor adjacent to the tubs is made of wood grating.

Concentration of the Acid: It is self-evident that different kinds and classes of material require different treatments in cleaning. For meeting these different requirements, there are three factors at the command of the cleaner, namely, time, temperature and acidity, or concentration of acid. Any or all of these factors can be varied, but as there is a certain temperature which is most satisfactory and since the time available for the cleaning generally depends, more or less, upon the size and type of crane used, the ability of the men to load buggies, put on and

take off yokes, place the pins of rods or wire in the acid, and perform other necessary operations, it is the practice to keep the temperature constant, and to adjust the acidity to the time available and the requirements of the material. In general, then, acid concentration for rod or wire cleaning is subject to wide variations, ranging from about 1 per cent. to about 7 per cent. Thus, in the case of low carbon rods, for example, basic stock takes a stronger acid than Bessemer stock, while all high carbon rods require a sharp, quick cleaning. If the rods are finished at a high temperature, a heavier coat of scale forms than when they are finished at lower temperatures, and more acid is needed to clean them. Even the make-up of the bundles may affect the amount of the acid required, for large compact bundles are more difficult to clean than loose ones. Similar statements may be made with respect to annealed wire, which as a rule, requires the use of a much weaker acid than the rods. In operating, the vats are first filled with water, and enough concentrated acid is added to give the acidity required, which may be determined by chemical or gravity tests, or estimated from the capacity of the vat and the gravity or concentration of the acid used. The steam is then turned on, and the temperature is raised to the desired point, which is ordinarily 180° F. As soon as cleaning operations begin, the acidity decreases, due to the action of the acid upon the metal, and it is necessary to add more acid from time to time to maintain a fairly uniform acidity. After the vats have been in use for a time, normally from 12 to 24 hours, the dissolved iron sulphate and suspended particles begin to interfere with the cleaning, so the entire contents are removed and the vats are started afresh.

Temperature for Cleaning: The importance of maintaining the temperature of the pickling solution at the proper point cannot be too strongly emphasized for the following reasons: The velocity of the reaction between metal and acid is greatly affected by the temperature, being about 100 times greater at 190° F. than at normal atmospheric temperatures. A high temperature, then, would appear to save both time and acid, but other factors enter to fix a limit to which the temperature may be raised. Thus, if the temperature is raised above 190° F. the gain in speed is, from an economic point of view, more than offset by the loss of steam and of acid carried away with steam. How serious these losses may be is illustrated by the fact that the loss of acid on this account sometimes amounts to 15 per cent. In addition, the loss of steel through direct action of the acid, not to mention the injury done to buildings and machinery and the discomfort of the men, is excessively heavy. Rather than to raise the temperature above 180° F. it is better to add more acid, increasing the acidity, when it is desired to hurry the cleaning.

Time of Cleaning: With the temperature fixed as stated above, it is impossible to clean in a given time or to meet all conditions by varying the acidity, so the time may vary within certain limits also. With a

given temperature and acidity, the time necessary to clean depends upon the size, kind and condition of the rod or annealed wire to be cleaned and also upon the condition of the acid solution. In general, this time varies from 10 to 30 minutes. To reduce the steel loss to a minimum, save acid, and avoid injuring the material and spoiling its surface, the bundles should remain in the acid no longer than is necessary to loosen the scale and dissolve the red rust. If rods are badly coated with red rust, it is sometimes a better plan to give them two cleanings, preferably allowing them to dry between these two treatments. The time element is especially important in the cleaning of high carbon rods or wires. The effects of the acid treatment in general, are more pronounced upon the high carbon material than upon the low carbon. If high carbon steel is etched too long or too deeply, the action of the acid may leave a carbonaceous deposit upon the surface, a defect, known as a "smutty surface," that may remain as a defect when the material is drawn into wire, and will detrimentally affect the life of the wire drawing die. Great care is also required in pickling high carbon stock to prevent pitting the surface.

Rinsing: As soon as the material has been properly cleaned, the pin of coils is hoisted from the acid vat and dipped into cold fresh water, contained in an adjacent vat or tank, to remove the acid. In order to dislodge any pieces of scale or other foreign substances adhering to the surface, a stream of water under high pressure is directed against the coils with a hose, for it is essential, to procure the best results in drawing, that the surface of the material be clean and free from all foreign substances.

Other Methods of Cleaning—Threshing: The method of cleaning described above, while universally applied to rods, is not suitable for cleaning all kinds of wire. Thus, for reasons which will be explained later, in cleaning wire preparatory to coating with zinc or tin, it is passed through a hot solution of hydrochloric acid instead of sulphuric. Other wires that must be cleaned in process are frequently hand cleaned by a method known as threshing. In this method the coils are first immersed in very dilute acid contained in small tubs. After remaining in this acid a suitable length of time, the thresher, or cleaner, with the aid of a hook, lifts each coil of wire out of its tub, raises it above his head and forcibly throws it down upon a steel plate to remove mechanically the dirt and scale adhering to the surface, after which operation he rinses the wire by dipping it into a tub of fresh cold water. This method is generally applied to the smaller sizes of wire which have been bright annealed and have a very thin coating of scale, such as process wire for mattress wire, weaving wire, or other fine wires, and high carbon wires that are to receive an extra finish.

Sulling: If the material is to be sulled, the pins of coils must be transferred from the rinse box immediately to the sulling rack, or if the two-crane system is used, to the conveyor over the sulling rack. Here

the coils are kept moist for a time by means of fine sprays of water. Through the action of this water, the oxygen of the atmosphere, and the traces of acid which may still remain on the material, the surface soon becomes coated with a faint brownish or greenish rust known as the sull or water-rust coating. This coating aids in lubrication and is very desirable in all cases where the material is to be given many drafts by dry drawing; but, as stated before, it darkens the color of the drawn wire and cannot be used to produce the brightest finishes on the coarser wires.

Coatings—Importance of: In drawing a rod or wire through a die, some sort of coating for the metal in addition to the die lubricant is imperative. If no coating were used, more power would be required for the drawing and the die would wear badly. Consequently, the surface of the wire would be scratched, and its section would vary greatly. Several varieties of coatings are in regular use, and the particular coating employed in any specific case depends on the kind and size of the wire to be made, the drafting and the finish desired. In dry drawing, the chief function of the coating is to serve as an absorbent and carrier of the die lubricant. For performing this function, the best substance so far discovered is dry slaked lime. This lime coating is cheap and easily applied, and besides acting as an aid to lubrication, it performs other functions, also. Being alkaline in character, it tends to neutralize any traces of acid remaining after the cleaning process, and protects the material from oxidation during the interval between cleaning and drawing, and also, to some extent, after the drawing. In wet drawing, the ordinary greasy die lubricants used in dry drawing are ineffectual, because they will not adhere to the wet wire, while the liquor or soap solutions used do not form films heavy enough to give the necessary protection in heavy drafting, hence the coating itself must serve as the principal lubricant, and in addition protect the material from oxidation during drawing operations. The coatings most practicable to use to meet all the conditions of wet drawing are the copper or copper and tin coatings already mentioned. The deposit of these metals on the wire forms a heavy film between the die and the wire, and, being comparatively soft, they materially decrease the frictional resistance.

Process for Lime Coating: The process for lime coating consists simply of dipping the pins of coils into slaked lime emulsion, or milk of lime, contained in a vat or tank, and permitting them to remain there long enough for the liquid to penetrate to the innermost strands of the coils. If the coils are not too compact, this requires but a few seconds, and care should always be taken to see that the coils are well opened before the pins are lowered into the lime vat. The slaked lime is made by treating burned lime, or calcium oxide, with water, when the well known reaction, $CaO+H_2O=Ca(OH)_2$, takes place, forming calcium hydroxide, a part of which will dissolve in excess water, while the remainder remains undissolved to form the emulsion. The lime should be dead burned and

of the best quality, and the emulsion must be kept free from ashes, cinders, and all gritty substances. The coating liquid is usually kept at a temperature of about 140° F., though cold lime coatings are occasionally employed. The consistency of the emulsion is regulated according to the thickness of the coating desired, which in turn depends on the nature of the work to be done upon the rod or wire.

Coatings for Dry Drawing: Usually, one coating and one application of lubricant will serve for a series of as many as four drafts. In general, the greater the number of drafts in such a series of drafts the heavier the coating must be. Also, the lighter the lime coating the brighter the finish, and the easier the wire can be cleaned, but the greater will be the liability of forming surface scratches and other imperfections. In the case of hard wires that require a bright finish, and can be finished in one or two drafts from the rod, the lime coating alone will be used, for sulling would darken the finish on the wire. When rods are to be given many drafts to finer sizes, they are always given a sull coat first and then a heavy hot lime coating. In such wires, this treatment of the rod will produce the ordinary bright finish. Another example of double coatings is what is known as the copper and cold lime coating. To apply this coating, the rods or wire, after being thoroughly cleaned, are dipped into a dilute solution of blue vitriol, or copper sulphate, then rinsed in water, and dipped into a cold emulsion of slaked lime and water, after which the coils are dried in the usual manner. This coating is used, in certain cases, as a primary coat for process hard coppered wire and process tinned wire, and is also applied to certain high carbon stocks to assist in the drawing.

Baking: The final treatment to which the material is subjected preparatory to dry drawing is baking. For this purpose the wet lime-coated coils of rods or wires are loaded upon metal buggies, which are then pushed into a kind of oven known as the baker or dry house. The modern baker is of the continuous type. It is constructed of brick and consists of one or more long, low-roofed compartments with steel doors at each end. They are usually placed between the cleaning and the wire drawing departments, so that the loaded buggies may be charged through the front door next to the lime vats and be pushed through to the rear door near the wire mill. To provide run ways for the buggies, steel tracks are laid between the front and rear doors. In some plants these tracks are inclined so that the buggies will move through by gravity, while in others the tracks are level and the buggies are propelled by means of mechanical pushers. The bakers are kept at a temperature of from 250° to 400° F., according to the kind and class of material being made, and the loaded buggies remain in them from 3 to 12 hours according to the kind of material and the conditions prevailing. They are heated with hot air, which is admitted to the bakers through openings in flues located beneath the tracks and, in some cases, overhead as well.

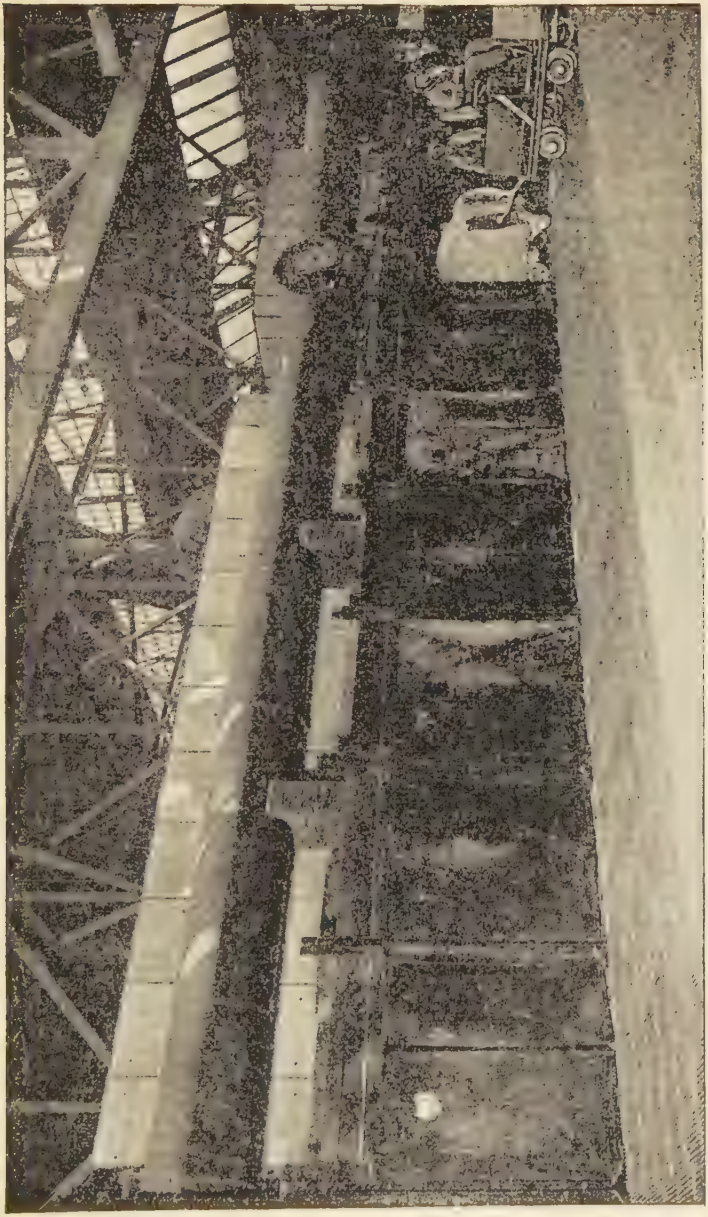


FIG. 233. The Bakers. Showing manner of handling loaded buggies.

Object of Baking—Acid Brittleness: The primary object in this baking is to thoroughly dry the coating, for if the lime wash is not dry it will fail to perform its chief function in the wire-drawing operation. For this reason the material is taken from the bakers as it is needed by the wire mill, and it should be drawn as soon as it has cooled to normal room temperatures. The second object of the baking is to remove the so-called acid brittleness, produced to a greater or less degree in the cleaning operation. This brittleness is produced by hydrogen absorbed by the steel while it is in the pickling bath, the gas being liberated by the action of the acid upon the metal. By baking the material for a few hours at the temperatures stated in the preceding paragraph, this absorbed hydrogen is driven out and the steel is restored to its original toughness. Pickling in hydrochloric, or muriatic, acid produces less acid brittleness than pickling in sulphuric, but the former is more costly, and also more objectionable in other respects than the latter, hence is seldom used for ordinary cleaning. For cleaning prior to galvanizing or tinning, hydrochloric acid is superior to sulphuric, and is universally used in these cases.

Coatings for Wet Drawing: As already stated, the coatings for wet drawing consist of a thin plating of copper or any alloy of copper and tin, obtained by dipping the perfectly cleaned wire in solutions of the sulphates of these metals. For the copper coat, the solution is prepared by dissolving blue vitriol in a suitable amount of water, and adding a very small percentage of sulphuric acid. For the brass coatings, the solutions are prepared by adding tin sulphate or feathered tin in varying proportions to the acidified blue vitriol solution. When the cleaned wire is dipped into any one of these solutions, a chemical reaction takes place between the iron and the dissolved salts, in which the metals in solution are precipitated or deposited upon the surface of the wire. For a pure copper sulphate solution the reaction is represented thus: $CuSO_4+Fe=Cu+FeSO_4$. And for a pure tin sulphate solution the following reaction takes place: $SnSO_4+Fe=Sn+FeSO_4$. When both of these sulphates are present, these two reactions take place together, depositing both tin and copper, if the conditions are right. The exact proportion of tin to add for the liquor finishes is, therefore, regulated according to the color desired on the finished wire. In this way it is possible to produce at will a highly polished and smooth coating of almost any shade of the colors ranging from white or tin through the brasses and bronzes to the red, or pure copper, color. In regular practice this coating is done just prior to drawing the wire, hence the cleaned wire is delivered to the wet wire department in the wet condition, and is kept immersed in acidulated water or fermented liquor contained in barrels until the mill is ready to draw it.

SECTION VI.

WIRE DRAWING EQUIPMENT.

Dies: In general the wire-drawing die can be defined only as a plate or body of some suitable material containing one or more tapering holes called "die holes." From what has already been said, it will be evident that this tool constitutes the one element indispensable in any wire-drawing equipment, and it should now be added that a good die is essential to the turning out of a satisfactory product. The elements of a good die may be said to be a smooth properly shaped hole in material having sufficient strength and possessing great wear resisting qualities.

Materials for Dies: The die material surrounding the die hole must be extremely hard to withstand the frictional wear of drawing the wire, and possess considerable strength to resist the pressure against the wall of the die hole; also the die as a whole must be able, when supported at the ends, to withstand the pull of the wire without bending or breaking. Only chilled cast iron and a few of the alloy steels or diamond mounted on a metal disc or plate will meet all these requirements. All three of these materials are used for dies, but each for drawing a different kind or class of wire from that for which the others are used, as will be explained later. The cast iron and steel dies usually have the form of a small rectangular plate as shown in Fig. 234, and usually contain a number of holes, though some steel dies contain but a single hole.

Die Holes: The shape of the die hole at the exit end will be exactly like that of the wire, but from end to end the size and, in some cases, the shape of the hole must vary. In other words, the hole must be properly tapered, to provide for a gradual reduction in the section of the rod or wire being drawn. The exact design of a hole through a cast iron or steel die is determined by the kind and size of the stock to be drawn, the speed of drawing, and other conditions, because for each set of conditions there is some one best shape for the die holes, and some speed best adapted for the drawing. To illustrate some of the chief features of die design, let us consider a hole in a cast iron die for drawing low carbon round wire. A section of this hole is shown in the drawing of Fig. 235. It will be observed that the inner surface of the hole is made up of four distinct zones. The first zone, on the entering side of the die, is somewhat larger in diameter than the rod or wire to be drawn, and is, therefore, formed when the die is cast, and is not machined; its purpose is to afford room for the die lubricant that adheres to the rod or wire to be drawn into the hole. The next zone constitutes what is known as the "smoothing out" zone, which is machined to finish. In this zone most of the reduction in section takes place, and its angle of taper is, therefore, its most important feature. The next two zones are also machined to finish; they are known as the "bearing" and the "countersinking." The bearing tapers very

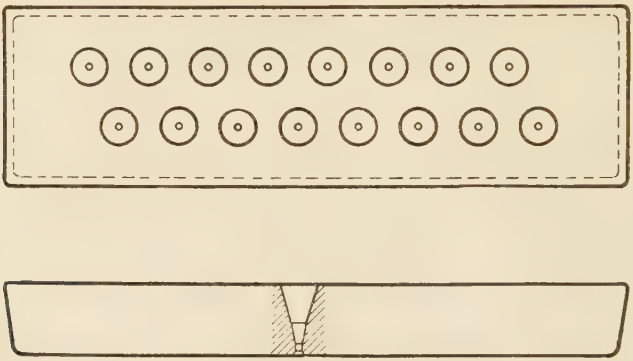


Fig. 234. Plan and Section of 2-Lb. 16-Hole Die

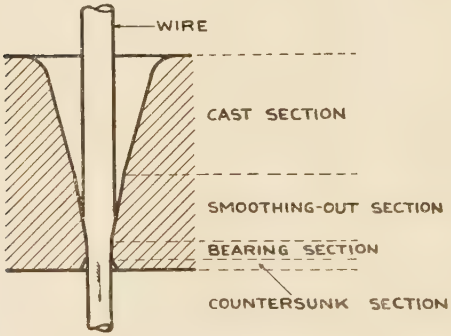


Fig. 235. Enlarged Cross Section of Die Hole Showing Names of Parts.

slightly toward its exit end, which determines the shape and size of the wire, while the object of the countersinking is to prevent this circular edge of the hole from breaking away.

Chilled Cast Iron Dies are made by casting white cast iron in metal molds or chills. As explained on page 440, chilling the cast metal gives an extremely hard and wear-resisting surface, which is much desired in drawing. The sizes and the number of holes the dies contain will be governed by the size and kind of wire to be drawn. For the coarse sizes of wire the dies will be larger and contain fewer holes than for the smaller sizes. It is necessary that the body of the die, or the die plate, be thick enough and that the holes be so spaced that the die will possess sufficient strength to withstand the pulling force of drawing. The tapering die holes are

cast in the die, and must later be finished by reaming in order to produce a smooth hole of the exact size and shape desired, as shown in Fig. 235. The entire portion of the die which the wire touches must be very smooth and free from flaws in the metal. It is, of course, essential to the life and the size of the die that the reaming operation be performed with great accuracy. Chilled iron dies are used in drawing soft rods from about .35 inch diameter and hard rods from about .3 inch diameter down to sizes as small as No. 20 gage. The difficulty of reaming holes smaller than No. 20 gage in cast iron dies is such that it is not practicable to employ these dies for sizes finer than this. After a die has been worn out for one size, it is reamed to a larger size, and this operation is repeated after successive periods of use until there is no further use for the die or until it breaks. Concerning the composition of the iron for these dies, this must be carefully regulated to secure the hardness and toughness desired in these tools. Besides the usual or common elements employed in chilled castings, some alloying elements may be used. No data is available to show the relative merits of the different mixtures used for this purpose.

Steel Dies: Steel dies are used for drawing all shape wire, all large wire, and for the wet drawing of most of the fine wires. The reason for using steel dies for fine wire drawing has already been given. In the case of shape wire, cast iron dies cannot be used on account of the impossibility of machining the holes to the exact size and shapes desired, while for large wire cast iron is lacking in strength to resist the great pulling forces required. The holes in steel dies for shape wire are hot punched, tapered and shaped up through a solid piece of steel. To shape up these dies for drawing, a series of taper driven punches, increasing in size and similar in cross section to the finished shape required, are used. For the common sizes of round wire the holes are machined to exact size and shape. As to the number of holes per die, single hole dies are generally used for shape wires and large round wires, but for common sizes of round wire each die will contain several holes, the exact number depending upon the size of the wire. Many of the steel dies which have cut out or become off size can be restored to original size by hammering around the exit end of the hole, and then punching out again to proper size and shape. From time to time it is necessary to anneal these dies in order to prevent their cracking from continual hammering and punching. For small wires, it is the practice to have each wire drawer set up his own dies and make his own tools, both of which require a good deal of skill and practice. The composition of the steels used for these dies will be found in the chapter on extra fine tool and special steels.

Diamond Dies are frequently used when exceeding accuracy and uniformity of section are required in the finer sizes of wire, especially in the process of continuous wet drawing. In the construction of diamond dies, a diminutive flat crystal of diamond is securely fastened in a center

opening of a small circular metal disc, then a hole of required diameter is worked through this diamond by means of special drills and diamond dust. Diamond is one of the hardest substances known and has great wearing qualities. Long lengths of fine wire can, in consequence, be drawn through these dies with little or no change of sectional area due to wear of the die.

Wire Drawing Frames: For the most part, wire drawing is accomplished by means of an equipment known as a Wire Drawing Frame. Each of these frames is composed of a **bench,** which is of table-like construction and is used to support the rest of the essential equipment; a **block** or **blocks** for drawing the wires through the dies; shafting, gearing, and clutches for starting, driving and stopping the blocks; **die holders** for supporting the dies during the drawing; **draw out** devices for drawing the first few feet of wire through the die or dies; and safety devices. Frames are usually referred to under two general classifications, as rod frames and wire frames, or in accordance with the sizes of the blocks they carry, as 22-inch frames, 16-inch frames, etc. Other terms employed are drawing-out frames, wet frames, fine-wire frames, etc., according to the class and type of wire-drawing they are designed for. Rod frames, as the name implies, are employed in giving the initial drafts to the rods, and are of heavier construction than wire frames, as the blocks which they support and drive are larger. Frames for drawing wire in the small sizes are generally constructed of wood, as frames thus constructed possess the obvious advantage of lightness. The weight of wire handled by wire frames is smaller per frame than the tonnage of material drawn on rod frames, and the reductions as a rule are not so heavy in drawing wire as in drawing rods; consequently, wire frames are not subjected to such severe usage as are rod frames.

Mechanism of a Frame: In the case of single draft drawing, the essential mechanical parts of wire drawing frames, whether used for drawing rods or employed for drawing process wire and fine wire, are practically the same for all. These parts and their arrangement, which are illustrated by Figs. 236 and 237, may be briefly described as follows: To begin, there is the main driving shaft; this is a horizontal shaft lying beneath and extending the entire length of the bench, and is supported by bearings attached to cross members connecting horizontal sills below the floor level. Connected with this horizontal shaft there may be one or more vertical shafts, commonly spoken of as spindles. Each of these spindles carries, at its lower end, a bevel gear which meshes with a mating gear on the horizontal driving shaft, and, at its upper end, a wire drawing block, which has the form of a flanged drum and, in service, revolves in a horizontal plane. Power for operating the frames may be and is applied by several different methods. In some cases the power is taken by belt from motor-driven line shafts located above, beneath, or on a level with

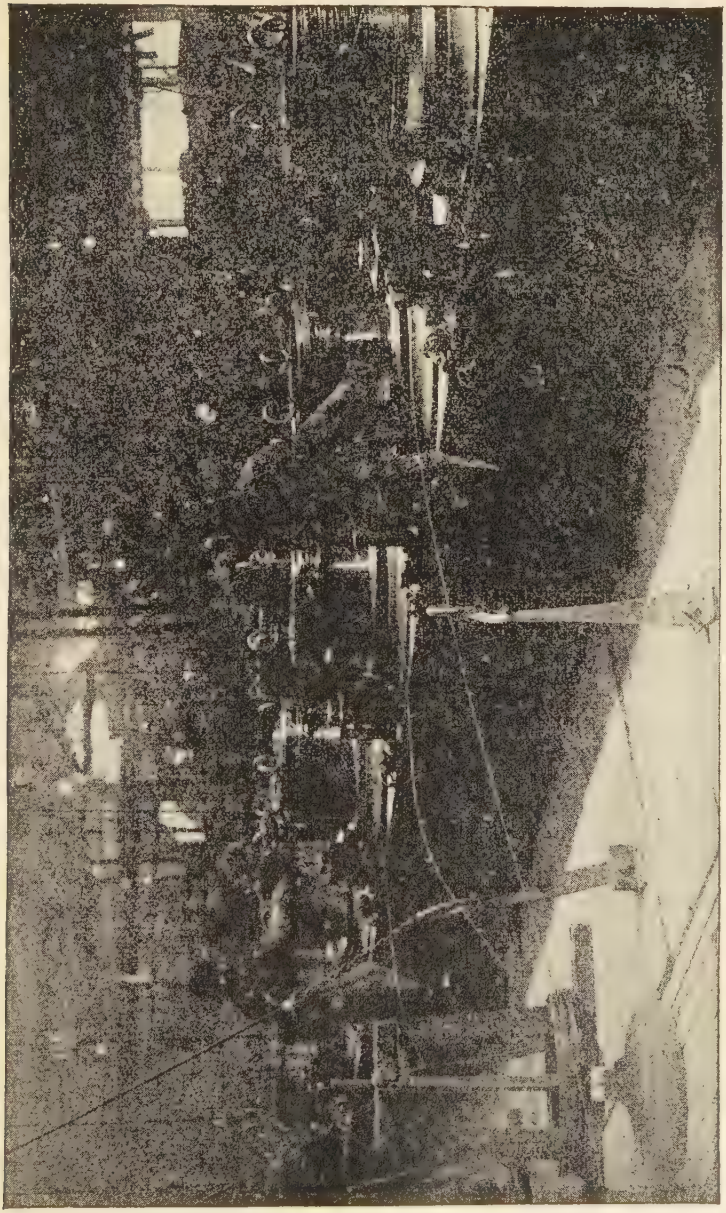


FIG. 236. Wire Drawing Frame in Operation.

the frames; in other instances each frame or each spindle is driven by an individual motor connected either direct or by belt.

Mechanisms for Driving the Blocks: In a case where several blocks are driven from a single shaft, it is necessary, and in all cases it is desirable, that means be provided for starting and stopping the rotation of the block independently of the driving force. To this end the large blocks are equipped with clutches, usually of the jaw type. With this type of clutch, two, three or four ears or lugs, placed on the bottom of the block, engage

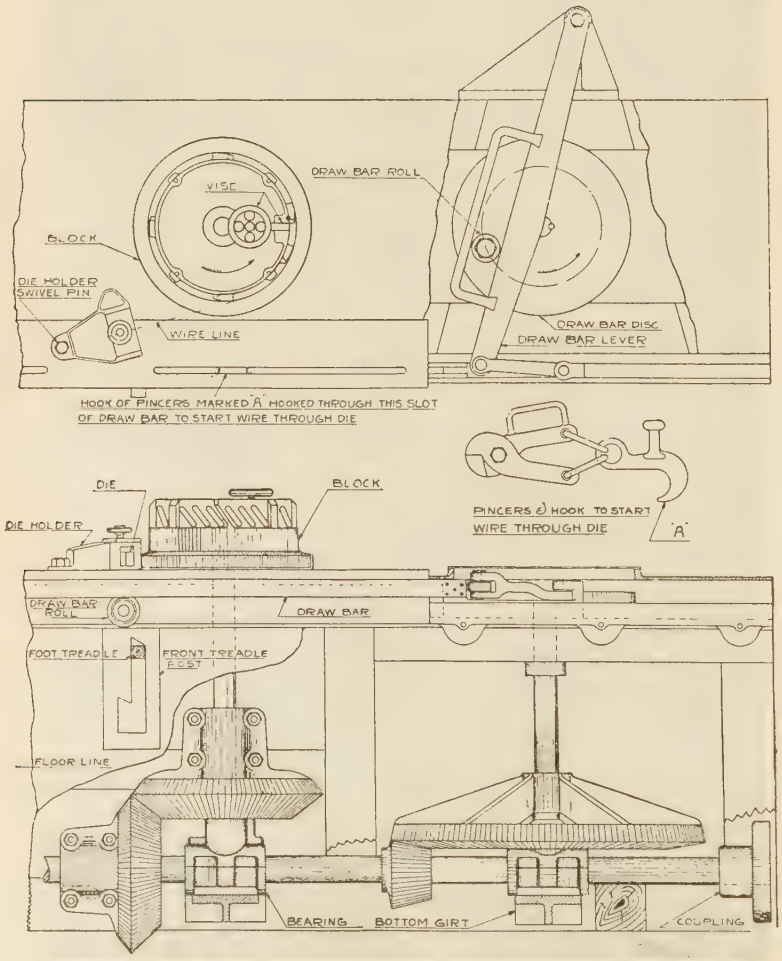


Fig. 237. Plan and Longitudinal Section of Typical Wire Drawing Frame.

similar lugs on a clutch disc or plate which is keyed to the vertical spindle. Thus, this clutch is engaged and disengaged by lowering or raising the block, itself, on the spindle which projects through its hub. For imparting this vertical motion to the block, two fingers, with rollers on their upper ends for supporting the revolving block, extend from a yoke below to the bottom of the block. This yoke supports a counterweight at its end, and is attached to a foot lever, through the agency of which the operator is able to start and stop the block at will. Small blocks are not equipped with these clutches, but, instead, the end of the spindle projecting through the block hub carries a pin which engages with a slanting slot in the block casting. During the operation of drawing, the tension on the wire holds this pin and the block in place, but when the coil has "run out," or in case the wire breaks, releasing this tension, the pin slips out of the slot and the block drops downward, thus disengaging the pin entirely, when the block soon comes to a stop. In the drawing of some kinds of wire, gradual acceleration at starting is most desirable, and for this reason some blocks are provided with friction clutches, or, in special cases, they are driven individually with variable speed motors. For very heavy work with rods of large size, large single machines, called "bull blocks" are employed, and these are actuated by individual motors. Also, in some modern installations smaller blocks are similarly operated.

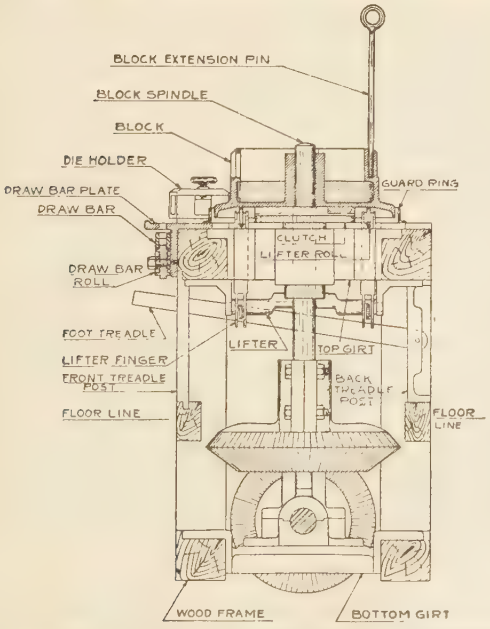


FIG. 238. Vertical Cross Section Through block of Wire Drawing Frame.

Functions and Sizes of the Blocks: The wire-drawing block serves two important purposes. Thus, while its primary function is that of pulling the rod or wire through the die, it also serves to form the drawn wire into coiled bundles of a convenient size. These coils represent not only a form of bundle that is most convenient for handling a ductile material of small section and great length, but also a form that produces the least distortion of the material, from the standpoints of both drawing and bundling. As to size, it is desirable to vary both the weight and the diameter of the coils. The weight of the

coils can be controlled only approximately by cutting the wire during the drawing, and exact weight bundles require additional and separate operations. The diameters of the coils are controlled by the diameters of the blocks. The first factor that determines the diameters of the coils is the size of the wire, for it is evident that a heavy rod or coarse wire should not be drawn on a block of small diameter, and the second factor is the desires of the consumers. Wire drawing blocks, therefore, are of various diameters. In general they range from 6 to 32 inches, but a large majority of them will be found within the range of 8 to 22 inches. The 22-inch blocks are used for drawing all wire down to about No. 15 gage, and are, therefore, looked upon as the standard for all coarse wire drawing. Rod blocks occasionally have diameters of 26, 28, 30 and, more rarely, 32 inches, but, as a rule, blocks larger than the standard 22-inch block are operated only in special work and are not to be mentioned as characteristic of general practice. While 6-inch blocks are used in drawing fine copper wire on certain types of continuous wire drawing machines, the smaller sizes of blocks in most common use for steel wire are 20-, 16-, and 8-inch. Some mills use 12-inch blocks, also.

Construction of the Standard 22-Inch Block: The 22-inch block not only represents a standard in size, but is also fairly well standardized as to construction. This block is illustrated in Figs. 237 and 238. From these drawings it is seen that the block has the general form of a hollow drum with a flanged base and a solid web bottom, the latter serving to carry a central hub through which the driving spindle projects. It is constructed of chilled cast iron, has an outside diameter of 22 inches at the base, and is about 7½ inches high. On the under side of the web, or bottom, are two or four ears which serve to engage the clutch on the spindle. Cast integral with the spindle hub and drum are reenforcing ribs, one of which is thick enough to carry the "screw down", or vise, for the purpose of gripping the end of the wire; also in these ribs are holes which carry the vertical extension pins used to retain the excess wire above the drum. Besides the pin shown in the drawing three more are carried by these ribs, equally spaced on the inside of the drum rim. On the outside of the drum, at the bottom, is a flange about 2¼ inches wide, the upper surface of which tapers towards the "fillet," which is the rounded angle between the flange and the drum. This fillet is necessary to cause the wire to slide up on the drum. The outer vertical surface of this drum is not exactly cylindrical but is rather a frustrum of a cone having a taper of about 7-32 inch per foot. The whole working surface of the drum is finished smooth. The taper and the smoothness are necessary so that the wire may slide progressively up the drum during the drawing operation.

Variations in Construction of Other Blocks: A detailed description of the various other sizes of blocks used would be too lengthy to be given here, for they are not standardized. It is sufficient to say that the

flanges, fillets, and drums are so designed as to handle the material drawn on them to the best advantage. Smaller sizes of blocks do not use extension pins to hold the coils in shape and position, but the drum is carried to a height sufficient to care for the size of the coils drawn. In the 8-inch blocks, a telescopic inverted drum is used with a flange on the upper edge, which fits inside the block drum, and so receives the overflow and prevents the accumulating wire from snarling.

Speeds and Spacing of Blocks: The speed at which blocks are operated varies in different mills, and also with the size of the blocks. The standard speeds for 22-inch and 20-inch blocks, running on soft stock, are between 45 and 70 r. p. m.; for 16-inch blocks, between 40 and 70 r. p. m. in wet drawing, or between 40 and 60 r. p. m. in dry drawing; and for 8-inch blocks about 85 r. p. m. Rod blocks are spaced 4 to 5 feet from center to center; smaller blocks at shorter distances. Spacing has depended more or less upon the ideas of the designer of the machinery, consequently, no definite standard has been followed in the installation at various mills. It is essential that enough space be given to permit the operator to work with safety and without being overcrowded. At the same time economy of floor space must be taken into account.

Pointing Equipment: In common practice, there are several methods of pointing rods and wire preparatory to drawing. Except in very large sizes, the work is generally done by the wire drawer himself. Wires, No. 20 gage and finer, are ordinarily pointed by simply pulling the wire until it breaks apart. As the wire stretches or lengthens before breaking, its size is usually reduced enough to permit threading through the die; if the wire does not stretch enough, it may be filed down to a size small enough to enter the hole. Shape wire is often pointed by heating and stretching, the wire retaining its special shape as it reduces in section. Common sizes of wire, or ¼ in. to No. 20, are usually pointed between a pair of small grooved rolls geared together in a housing and operated by a crank shaft causing them to make half revolutions. These rolls are placed on or near the drawing frame. The end of the wire is entered in one of the grooves, drawn in and expelled by the motion of the rolls, then turned and repeatedly entered in smaller grooves until it has been satisfactorily decreased in size. Rods and large sizes of wire are frequently pointed in a swagging machine, or so-called "rotary pointer," which has a rapidly revolving head provided with mechanism for swaging the wire. Very large sizes, either round or shape, are heated and forged or are machined in a lathe or milling machine to smaller size.

Die Lubricants: In addition to the wire coatings already described, all wires in dry drawing require some form of lubricant. This material is usually placed in the die holder, so that the wire will have to pass through and continually mix the lubricant before entering the die hole.

The lubricant is needed to prevent excessive heating and wearing of the die, to produce a smooth bright surface free from scratches, and a wire of uniform section. As explained elsewhere, it is necessary in most cases to lubricate the wire for only the first draft of a series, since enough lubricant will remain on the surface to serve for several subsequent drafts. Various substances are used for this purpose, such as the specially prepared greases or drawing compounds, tallow, pulverized soap, or oil mixed with meal or flour. The particular kind of lubricant used in any specific case will depend upon the size and kind of wire to be drawn, the kinds of finish desired, the ideas of the workman, and so on. In continuous fine wire-drawing, soap water is extensively used, the wire being immersed or otherwise kept wet during the drawing process, while in other wet drawing, the liquor serves as a lubricant.

Draw-Out Equipment: The frames used for drawing rods and coarse wire are all equipped with devices known as draw outs for pulling the first end of the coil through the die. There are several forms of these draw-outs in use, and as none may be considered standard and one of these is plainly illustrated in Fig. 237, it seems inadvisable to describe them in detail here. On the larger blocks, the end of the coil, after being pulled through the die by the "draw-out," is gripped between two jaws forming a part of the block, the lower one fixed and the upper one screwed down by a small hand wheel. On the smaller blocks the wire is pulled through the die by hand, wrapped around the block a few times, looped through a hole on the upper edge of the inner drum and secured by twisting.

Safety Devices: Modern rod frames are so equipped with safety devices that serious accidents are practically impossible. Automatic stops are provided for each block so that, should a man be caught, his body will trip a lever, release a counter-weight, or actuate a friction belt arrangement which in turn acts on the block-stopping mechanism, raising the block and disengaging it from the clutch. These devices vary in details with different mills.

The Drawbench: A drawbench is a mechanism used to give a single draft to heavy material, which is afterwards usually straightened and cut to a definite length. It handles the largest sizes drawn and is especially adapted for drawing shapes, screw stock and small shafting. The machine itself consists of a horizontal framework 50 to 100 feet long, through the center of which runs a heavy flat bar roller chain driven by heavy sprocket wheels. The die through which the material is drawn is located at the opposite end of the frame from the drive. A carriage mounted on wheels, and so arranged as to travel along the upper surface of the frame or bench, is provided with suitable jaws for gripping the material and pulling it through the die, and also with a heavy hook for connection with the roller chain. This equipment is similar to that used for drawing seamless tubes. (See Fig. 330, page 1102.)

Continuous Drawing: A notable innovation in wire drawing machinery is that effected through the employment of the continuous principle, by which the wire is drawn through a succession of dies simultaneously, the number of drafts being limited by the amount of reduction possible before the wire requires annealing. When everything works well, the continuous drawing process eliminates the handling of bundles between drafts, an important consideration, especially in coarse wire drawing, but when trouble ensues, a condition not possible entirely to avoid, then a larger portion of the drawing equipment will be nonproductive than in single draft drawing.

Principles of Machines for Continuous Drawing: The amount of reduction in each die is limited by the amount of strain which the reduced wire will stand without injury, and it is, therefore, impossible to draw the wire through a series of dies by applying force to the finally reduced wire. This difficulty is overcome by placing a power driven block or drum behind each die, and winding the wire two or three times around each intermediate drum in succession. In this manner a pull is obtained from each drum sufficient to draw the wire through the die placed in front of it. But even with this provision the problem is still complicated by the fact that the ratio of the speeds of the various sections of wire in a series of reductions may not remain constant, causing slippage of the wire about some of the drums, unless provision is made whereby this slipping is prevented. Slippage not only represents waste power but it may also cause injury to the surface of the wire, or it may wear the coating of the wire, or both. The change in the speed ratios is due to the wear on the die hole, which may be either enlarged through "cutting out" or decreased in size from an accumulation of minute particles "shoving up" on its inner surface. The change is therefore, cumulative, hence, difficult to overcome.

The Slipping of the Wire can be minimized by means of machines employing two different principles. In one class of machines for attaining this end in coarse wire drawing, either the diameters or the speeds of the successive drums are made to vary in the inverse ratio of the cross sectional areas of the wire, irregular variations in these ratios being taken care of in one of several ways. In one machine, this variation is cared for by differential gearing placed inside the blocks; in another, each block is controlled by a separate driving motor, so regulated that its speed will vary inversely with the load. And in still another type of machine two or three smooth-faced blocks are formed on a single solid casting with diameters varying as near as possible with the theoretical speeds of the wires, and any slight amount of slippage resulting is deliberately permitted.

The Second Principle used in meeting this problem of slippage depends upon the handling or manipulation of the loops. In one group of such

machines there are either a certain number of "idle" loops, or of "controlled" loops whose number and length fluctuates with the wear of the die, and the mechanism automatically increases or decreases the number of loops, or the length of loops as the wire speeds change. These devices have not thus far been very successful for the drawing of coarse wire. In a more recent development, having certain advantages, the wire is uncoiled from above the first block, and is extended down through the hollow spindle of this block, thence through the second die onto the second block, and so on through the whole series. Other schemes have been tried, but the foregoing will serve to show the general principles underlying continuous drawing, along which designers have been working.

Continuous Machines for Fine Wire: The continuous drawing machine for the wet drawing of fine wire is very compact and more nearly standardized. The drums are arranged over a tub of soap water which serves as a lubricant to the wires passing through the water. Each one of the revolving drums, beginning with the second, is driven faster than the preceding one, the increase in speed being sufficient to take up all the elongation of the wire and allow a very small amount of slip in addition. When the wire leaves the last revolving drum, it is passed through a finishing die, and the power derived from the vertical drum on one side is sufficient to pull the wire through the last die and to coil it.

Use of Continuous Machines: While there are several forms of continuous drawing machines, the underlying principles are much the same in all. In certain of them, it is possible to reduce wire some twenty sizes in one continuous operation. Continuous drawing has proved much more successful for copper than for steel wire, the latter being so much hardened by the process as to increase greatly both breakage of the wire and wear on the dies.

SECTION VII.

WIRE DRAWING PROCESSES AND OPERATIONS.

Results of Cold Drawing: In a previous section we have attempted to give a general description of the various wire drawing processes and operations, and we now purpose to give these operations more in detail. Before taking up this detailed description, however, it seems advisable to consider the results attainable and the effects produced by the wire-drawing process, itself. Concerning the results attainable by the wire-drawing process, these may be summarized as follows:

1. By this process metal may be elongated and reduced in section to an extent not attainable by any other method.

2. By this process a greater degree of accuracy as to size and section

can be attained than is possible by any other method excepting cold rolling, which is not applicable to common sizes of wire or fine wire.

3. The process is capable of producing a uniformly smooth and highly polished surface.

4. The process serves as a more or less sure test for the detection of hidden flaws in the metal. The fact that a wire has satisfactorily withstood the drawing operation may be taken as a reliable indication that the metal was originally sound and free from defects liable to cause it to fail in service. This statement does not mean that the wire itself is free from all flaws or defects, for it is possible to produce certain flaws by improper drawing.

5. Finally, the process affects the physical properties of the metal, which fact, as noted under the heading of tempers, makes it possible, by employing this process in conjunction with heat treatment, to produce many wires having different mechanical properties from the same steel, independent of its composition.

Effect of Drawing Upon Physical Properties: Cold drawing, like cold rolling or other methods of cold working, invariably increases the hardness, stiffness, tensile strength, and elastic limit, and, at the same time, decreases the ductility, that is, the elongation and reduction of area, and, to a slight extent, the electrical conductivity of the metal. This statement applies to copper and other metals, as well as to steel. The extent of these changes of properties is not always directly proportional to the amount of cold work done upon the metal, as it is affected by various factors, such as total measure of drafting, number of drafts by which this total is reached, and the nature of the material itself. However, the wire drawers have determined from long experience what the total effect is for a great many different sets of conditions, so that if the conditions of manufacture are known, the physical properties of the finished wire can be estimated with a fair degree of accuracy.

The Cause of These Changes: These changes in the characteristics of the metal brought about by cold working are to be attributed to the changes in grain structure such working produces. In a hot rolled rod or in an annealed wire the grains are arranged in a comparatively regular manner, as shown in Fig. 240, p. 892. The grain arrangement of an annealed low carbon steel wire is shown in the photomicrograph of Fig. 243, page 893. These are photographs of small sections as viewed through a microscope which enlarges the area viewed 100 times. All photomicrographs shown represent longitudinal sections, or side views, that is, the wires are viewed at right angles to the direction of drafting, the direction of drafting being horizontal in the photograph. Fig. 240 exhibits the comparatively regular disposition of grains in the steel before drafting. Fig. 241 shows the condition of the grains after the material has had one draft.

Here it can be seen that, as the wire is being elongated while passing through the die, the grains in the steel actually become elongated, also. The grains elongate in the direction of the drafting and become correspondingly narrower at right angles to that direction. Fig. 242, page 893, shows the same wire after having had a number of drafts. Here the grains have been stretched to a considerable extent. Due to the stretching of the wire in drawing and the crushing effect produced by the pressure exerted by the die in all directions towards the center of the wire, the structure has become so altered that it is difficult, if not impossible, to locate the exact boundaries of the individual grains in their strained and distorted condition.

Limitations of Drawing: Steel may be drawn several drafts further than the state illustrated by Fig. 242, but when wire has been put into this highly strained condition by drawing, it loses its ductility to such a degree that it is not practicable to submit it to further drawing, and if required to be reduced in section still more, it becomes necessary first to restore the grains to a comparatively regular arrangement. This changing back of the grains to their regular or normal form simultaneously restores the properties that existed in the wire before it was subjected to drawing. The processes employed for restoring the grain to the regular formation are annealing and patenting. The effects of these processes will be discussed in the Section on Heat Treatment of Wire. Enough having been said to explain the reasons for them, we will now consider some of the chief features of wire drawing practice.

Dry Drawing Low Carbon Coarse Wires: Steel wires drawn by the dry process can be roughly subdivided into three groups according to the number of drafts given them. The first group includes all one-draft wires. These wires are made for manufacturers who require a bright wire of low temper for swagging, upsetting and some forming, such as for bolts, rivets, screws and so on. The second group consists of two-, three- and four-draft wires. Some of these wires may be used for hardware purposes; some, for galvanized wire for fencing, for bale ties, and for telegraph and telephone lines; and some for certain process wires which will be treated according to the requirements and reserved for subsequent drawing to fine sizes. The third group consists of five-and six-draft wires, most of which are process wires and represent about the limit of commercially successful drawing from a No. 5 rod without annealing.

Drawing Single-Draft Coarse Wires: On single draft wires as light a coating and lubricant is used as is possible to meet the needs of each case, the exact nature of both coating and lubricant depending upon several conditions, such as size and kind of stock, uses to which the wire is to be put, etc. These wires are generally drawn on 22-inch blocks, and each wire drawer is usually allotted two blocks, but on very coarse sizes only one block is operated continuously. Most mills now provide "block

strippers" which are small electric or hand operated hoists erected over the blocks, for lifting the heavy bundles off the blocks and onto buggies. This improvement saves the workers a great deal of hard labor. The usual speed of drafting on this class of product is from 25 to 60 r. p. m., or 144 to 346 feet per minute. The reduction in size of this one-draft wire is usually about 1-32 inch in diameter, and varies according to the purpose to which it is to be put. For bright finish wire, the principal object of the drawing is to remove the inequalities in dimension and finish of the hot-rolled rod and at the same time to retain as far as possible its physical qualities. If the light draft necessary to accomplish the first result would render the wire too hard for the purpose intended, the requisite softness is obtained by using a steel with very low carbon content or by using an annealed wire for drawing.

Drawing Two-, Three-, and Four-Draft Wires: In this second group of dry drawn wires are found practically all the process wire for finer sizes and the largest tonnages of finished wire. For the two-draft wire, the rod may be given a medium lime coating with or without sull, according to the finish desired; while for three and four draft wires, a sull coating and medium or heavy lime coating are needed on the rod. A lubricant of such character and consistency should be used with the first draft, that all succeeding drafts may be effected without damage to the wire or die. It will readily be understood that the reduction per draft, the speed, output per man, and other such features will vary for this class of wire, as well as for other kinds, with different companies and in different mills, but the following example represents conservative practices: Starting with a No. 5 low carbon rod, this would be drawn to a No. 8¼ wire on the first draft, to a No. 10½ wire on the second draft, to a No. 12 on the third draft, and to a No. 13½ on the fourth draft,—all on 22-inch blocks. The corresponding percentage reductions would be approximately 41, 35, 32 and 34, for each draft. Ordinarily, in two-draft work one operator handles two blocks; in three-draft work, three blocks; and in four-draft, four blocks, although in each case the wire drawer frequently operates one block more than the number of drafts. In spite of this fact, however, the output per man decreases as the number of drafts increase, being about half as much on four-draft as on two-draft.

Drawing Five- and Six-Draft Wires: The third group of wires are given their finish drafts on 16-inch blocks running at a peripheral speed of from 160 to 250 feet per minute, and are used for making both finished wire and process wire. In this group are found the hard drawn wires which have already received three or four drafts on 22-inch blocks and are to receive one, two or three drafts to No. 15, 16¼ or 17½ gage, and also those wires which were annealed at about No. 13 or 13½ gage and, after cleaning and suitable coatings, are to be drawn five more drafts dry to about No. 20 or 20¼ gage. No. 17¼ gage size represents practically

the limit of dry drawing without annealing, otherwise an excessive breakage would result, although in exceptional cases and with special care it is possible to draw Bessemer wire direct to No. 20 gage without intermediate annealing.

Drawing No. 14, 15 and 16 Wires: In addition to the wires discussed in the two preceding paragraphs, there is a relatively large tonnage of wires drawn four, five and six drafts from the rod on 22-inch blocks without process annealing. The most important of such wires are No. 14, drawn four drafts from the rod on 22-inch blocks, and five-and six-draft No. 15 and No. 16, drawn the same way.

Drawing High Carbon, or Special Wires: The class here referred to as high carbon wires is made up of a great variety of wires used for many different purposes. These wires include the four different grades of rope wire, the various kinds of spring wire, as well as music wire, spoke wire, brush wire, card wire, pile wire, pivot wire, safety pin wire, sewing machine needle wire, phonograph needle wire, and various other highly specialized products. Because these wires are made to specifications somewhat out of the ordinary, either as to finish or physical properties, requiring special treatment at some stage in their manufacture, they are collectively known as special wires. As to the method of drawing, the actual processes for drawing these wires do not differ from those for drawing low carbon wires except as to details, and such differences as do exist are due to the greater care that must be exercised with the high carbon wires. These differences may be summarized as follows:

1. In the case of high grade products, such as music wire and the better grades of rope wire, the rods are either annealed or patented before they are drawn. These treatments refine the grain structure of the rods, make them more nearly uniform as to strength and hardness, and provide better drafting qualities.

2. The cleaning of high carbon rods or wire requires greater care to avoid "smutty" surfaces and to prevent acid brittleness, which has a more harmful effect upon high carbon than upon low carbon wires.

3. The coating must be heavier and more uniform on the high carbon stocks in order to prevent scratching of the wire and cutting out of the dies.

4. A longer time of baking is required to counteract the effects of the cleaning acid.

5. As a lubricant for drawing high carbon wires, a specially prepared soap powder is used, as the very best lubricant possible is necessary for satisfactory results in drawing.

6. The speed of drawing and the amount of reduction per draft must be carefully regulated in order to prevent the structure of the wire from being harmfully affected by the drawing.

7. High carbon process wires are usually patented instead of annealed, whenever it is necessary to remove the hardening effect of previous drafting. This special heat treatment, which will be described later, provides in the case of high carbon wires, better drawing qualities and produces a much stronger and tougher finished wire than annealing. This treatment, when followed by proper drafting, gives the highest tensile strength of which the metal is capable.

8. As is well known, the higher carbon steels are more sensitive to heat treatment than the low carbon steels, hence they require correspondingly greater care in heating and cooling. Not only must too high temperatures in heating be avoided, but care must be taken to maintain uniformity in temperatures and rate of cooling in order to obtain uniformity in the finished product, which is particularly important and desirable in the case of the uses to which most high carbon wires are put.

Wet Drawing: As already indicated, wet or liquor finish drawing is applied to all wires smaller than No. 20 gage and to all coarser wires requiring a liquor finish, and is distinguished from dry drawing by the kind of coatings given the wires and the fact that they are drawn wet from a vat of liquor made of rye meal, flour and water, which has been allowed to ferment. As to the actual operation of drawing, the wet process does not differ from the dry, except that little or no lubrication is needed other than that furnished by the metallic coatings and the liquor. The percentage reduction per draft, however, is materially less in wet than in dry drawing, and it is evident that, of the two processes, wet drawing is the more expensive. For this reason it is the practice, in the case of coarse wires, to draw the wire dry to within one size or a half size of the finish before coating and drawing wet to finish. The size to which fine wires are drawn dry before coating and drawing wet depends upon the size of the finished wire and the purpose for which it is to be used, but generally the dry drawing will stop at about No. 17 or No. 20 gage, the latter representing the usual limit for dry drawing.

Manner of Handling Material for Wet Drawing: Concerning the method of handling the material for wet drawing, all wire, after being cleaned, is delivered, as previously stated, to the wet wire department immersed in water contained in barrels or tubs, where it remains until the mill is ready to draw it. Just before drawing, each coil of wire is removed from the water and dipped into a coating solution of the correct composition to give the kind of coating desired. If the wire is to be finished by single drafts, the coil is then placed on a reel set in a tub containing the fermented rye meal liquor, from which it is drawn wet through a die of correct size and kind by means of a block of proper size and strength. If the wire is to receive several wet drafts, the drawing may be done on a continuous machine. These machines give much more satisfactory service in wet than in dry drawing, because the drums may be partly sub-

merged in the liquor which keeps the wire cool. While the coating and liquor are generally relied upon to supply the necessary lubrication, occasionally, after coating, tallow will be rubbed on each coil at one or two places, and large sizes of wire are sometimes dipped in soap water, to supply additional lubrication. As to the composition of the coatings, the brass, or copper and tin, coatings give a better wearing, or drawing, surface than the pure copper coating, and these coatings, are therefore, used in all liquor drawing, especially of high carbon wires, unless a copper-colored finish is required. The drawing operations have the effect of burnishing the coatings so that the wire has a fine finish, but, while these metallic coatings cover the wire completely, they are extremely thin and cannot be relied upon to give much protection against corrosion.

Number and Sequence of Operations for Fine Wire Drawing: Enough has already been said to show that a great number of operations are required to produce a wire of very small size, and also that these operations vary in number, kind and sequence, according to the size of the wire, the kind of steel it is made of, and the purpose for which it is to be used. No one kind of wire, therefore, can be taken as typical of all fine wires, and space is not here available for describing in detail the manufacture of even a few of the more common. However, it seems desirable, at least, to attempt to give some idea of the great amount of work required to produce these wires, and apparently, the only way to do this is by an example. For this example we select a No. 34 low carbon wire, which, as fine wire goes, is produced in relatively large tonnages. Beginning with the steel, this wire, as is practically all low carbon fine wire, is made of Bessemer stock, for this steel usually shows good drawing qualities and is better suited, generally, to this class of work than any other kind or grade of steel. After this steel has been properly made and cast into ingots, it is soaked, and rolled into billets, which are reheated and rolled into the standard number 5 rod, each rod coil weighing at least 175 pounds. This rod is now cleaned, sulled, lime coated, and baked, after which operations it is given three dry drafts to No. 13 gage on 22-inch blocks, and each coil or bundle is cut in two by the wire drawer. The divided bundles are next annealed, following which process they are again cleaned, lime coated, and baked, then dry drawn through five die holes to about No. 20 gage on 16-inch blocks, the bundles being again cut in two. These smaller bundles are now pot annealed, special precautions being taken to permit the formation of as little scale upon the surface as possible. This bright annealed wire is now dip-cleaned or threshed, placed in barrels of water, and taken thus to the wet-drawing department. Here the clean bright wire is given the proper metallic coating, placed on the liquor reel, and drawn, one draft, wet on 8-inch blocks to about 21 gage, the direction of the wind being usually reversed. Thereafter the wire is given seven more wet drafts on blocks of the same size to 34 gage. The drawing operations

having now been completed, the wire is inspected and tested, when it may be shipped as bright wire without further work, or be tinned, galvanized, or annealed as required by the purpose for which it is intended. Low carbon wires much coarser than No. 34 gage may be given but a single anneal in process, usually between the dry and wet drawing, or the two annealings will be located at points different from those given in the series of operations described above, while wires much finer than No. 34 will be given three annealings in process, as No. 40 is about the limit it is possible to draw with two annealings.

Drawing Copper Wire: While this book is concerned only with the drawing of steel wire, a few words concerning the drawing of copper wire should be included, perhaps, especially since many of the wire manufacturers regularly draw wire from both of these metals. As to the actual drawing operation, the drawing of copper wire differs from that of steel wire only in minor details. Copper rod or wire is never coated. It is merely dip-cleaned in sulphuric acid to remove the oxide, then washed with a hose and dipped into hot water, the last operation being employed so that it will dry quickly. Fine sizes in coils, however, may require an additional operation, as they are usually dried in bake ovens. As the lubricant for the dry drawing of copper wire, tallow or tallow mixed with a drawing compound, is used. To anneal copper wire after hard drawing it is heated to redness and cooled either rapidly or slowly. Most of the copper oxide scale can be removed by quenching red hot copper wire in cold water.

Precautions in Drawing—Proper Alignment of the Die: The correct setting of a die is an important part of a wire drawer's work to which too much attention cannot be paid. As indicated in the drawings of Fig. 237, p. 870, and the accompanying Fig. 239, the die holder is fastened to the frame by a bolt allowing a lateral swinging movement. The pull of the wire is on a line from the center of the bolt to the fillet at the base of the block, and the face of the die should be at right angles to this center line. The hole through which the wire is drawn should so be in line that the center line of the hole will coincide with the pull of the wire, or with a line drawn from the center of the bolt holding the die box at a tangent to the block. Suppose the wire drawer carelessly uses a hole at one side of the center. The die box swings around, but if the center line of the hole does not coincide with the pull of the wire, off-sized or scratched wire will be produced, and the die will speedily wear out. The attached sketches, Fig. 239, show these two conditions. The upper sketch shows two positions of the die holder. The position shown by the solid line is assumed when wire is being drawn through a hole of a die which is placed correctly in the holder. The line CD represents the center line of another hole in the same die. If the wire drawer starts to draw a piece of wire through hole CD without moving the die to bring it into a central position

in the holder, the holder will assume the position shown in dotted lines and its center line will not be tangent to the block and center line CD will then not be tangent to the wiredrawing block. This is illustrated in the larger sketch at the bottom. The wire is there shown drawing off the lower edge of the die, and thus off-sized wire will be produced, and it is obvious that the life of the die will be shortened. The die should also be set in an upright position. Sometimes the clamping screw is not in just the proper position, and a bar of steel is used to shim it up, which is allowable only if properly used. The die should be lined up a little below

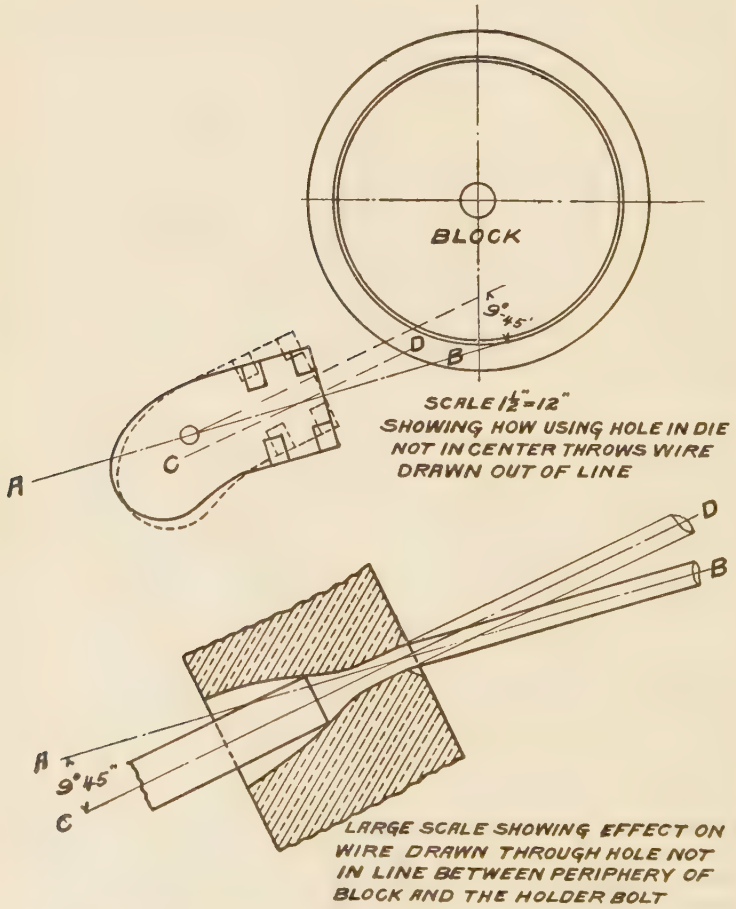


FIG. 239. Drawings Illustrating the Importance of Proper Alignment of the Die in Wire Drawing.

the fillet of the block. This will permit the leading of the wire on the block in such a way as to cause it to slide up properly. Some die holders are equipped with a hinged joint to permit a motion in a nearly vertical plane. This is to overcome the tendency to pull hard on the upper side of the hole when the block is first started. This tendency is due to the fact that the vise is usually on the top of the block and the pull is upward.

Drawing Limits and Tolerances: Although every effort is made to draw the wire as true to the required shape and size as possible, exactness in these respects is almost impossible under commercial conditions, and all wire produced under such conditions will vary some in diameter and section. These variations may be due to a varying degree of hardness in the metal being drawn, to somewhat rapid wearing of the die, or, in the case of wet drawn wires, to unsuitable or imperfect coatings. Some tolerance is necessary, therefore, but it is important that these tolerances be kept within certain limits defined by the use to which the wire is to be put. It is the practice of the American Steel and Wire Company to work to three sets of allowable variations in diameter of round wire, which are applicable to different kinds or grades of wire and are designated as "regular," "special," and "extra special" tolerances. Each of these sets of tolerances contain the variations allowable, which are adjusted to the size of the wire. In the "regular" tolerances, the allowable variations range from .001 to .003 inch; in the "special," from .0005 to .002 inch; and in the "extra special," from .0005 to .001 inch. In each case the larger allowance refers to coarse sizes and the smaller to the fine sizes, while for intermediate sizes variations intermediate between these two figures are permitted. Other manufacturers may have other practices in regard to these matters. All wire is gaged carefully in two or three places just after the first end of the coil is pulled through the die, and at the finished end, to insure that it is of correct size and shape. Wire ordered by gage number is gaged with a "V" gage, and sometimes with a micrometer to check the "V" gage. If ordered by decimal or fraction of an inch, it is gaged with a micrometer gage.

Straightening and Cutting Wire: With the exception of the largest sizes, all wire, both round and shape, is drawn on a block and, therefore, at the finished size, is still in the form of a coil. But for certain purposes it is desired to have the wire furnished in short straight lengths, rather than in coils. This straightening and cutting work is usually done on some type of machine.

Whirls: For common round wire, automatic machines are employed for straightening and cutting the wire. These machines are required to perform three operations simultaneously or in very rapid succession, namely, pull the wire forward, straighten it, and cut it into the lengths desired. The mechanism for straightening the wire is known as a "head" or "whirl." It contains a number of staggered dies which bend the wire

slightly, as it passes through, in reverse directions so as to remove the bends and kinks and leave it straight. The wire to be straightened is automatically fed through the whirl and onto an apron, where it actuates a mechanically or electrically driven cutting tool which cuts the wire into uniform short pieces of the length desired.

Bench Straightening: On very large sizes ranging from ¾ to 1 inch, which are too heavy to be cut on the automatic machine, the so-called bench straightener is used. With this machine the wires are straightened through a whirl which is fastened to one end of a bench that may be more than 100 feet long. The wires are pulled by power along this bench and cut into the desired lengths by shears, controlled by hand.

Roll Straighteners: For shapes and flats the roll straightener is used. This machine consists of a set of vertical and also of horizontal rolls which can be so adjusted that pressure can be brought to bear on the sides, top and bottom of the wire. On these machines the first sets of rolls put a considerable bend in the material to remove the kinks, and succeeding sets of rolls reverse this bend just enough to leave the wire perfectly straight. Squares, rectangulars and hexagons, narrow flats that are not too thin, most shape wires, and also very fine wires, provided the machine is properly designed for them, can be straightened on this type of machine.

Stretching Machines: A process of straightening by stretching is used on some fine soft annealed wire. The usual products straightened in this manner are copper wire, which may be as coarse as No. 15, and tinned tag and florist wires, from No. 20 to No. 35 gage and soft annealed. To straighten such wire it is wound onto a wheel about 8 feet in diameter, and the coil is then slipped off and placed over two lugs on a hydraulic machine. When the ram of the machine is set in motion one of the lugs moves away from the other, first drawing the coils out straight then stretching the strands some three or four inches. The stretched and straightened strands, which may number as high as 1,000 on the smaller sizes, are then cut to length. This process does not produce wires that are so straight or that are so exact and uniform in length as the other methods.

Importance of Inspection: Of equal importance with the various processes in making wire is the thorough system of inspection and testing to which the material is subjected during its progress through the mill and after finishing. Beginning with the hot-rolled rod, the material undergoes frequent and careful inspection during manufacture and is subjected to whatever tests are needful to determine its fitness for the service required. This system of vigilant scrutiny and rigid testing has come to be an indispensable aid in manufacture, and is obviously of great benefit to the buyer.

Final Tests on Wires: Wire for shipment to customers is regularly inspected and tested at both ends of each bundle for size, finish and temper. For temper, small sizes are tested by a kink test, medium sizes by a bending test, large sizes by a nick and break test. The better grades of wire are subjected to a machine test for tensile strength and elongation, and some of it may be given severe torsion tests. All telephone and telegraph stock is tested also for conductivity. All exact weight bundles are net weight of wire, excluding wrapping material. Wet drawn wires are invariably papered, that is, bundles are covered with paper, but they are also burlapped when so ordered.

Defects in Wire: After the wire has been drawn, it may be found defective or unsuitable for the purpose for which it was intended, and while every effort may be made to detect and discard all such wire, it occasionally happens that, due to lack of proper information, wire will be shipped that will not meet all expectations of the customer. It is, therefore, important that all concerned should know what the chief sources of trouble are so that all may cooperate to eliminate them. The complaints on wire can usually be placed under the following headings: Off size or shape, internal defects, surface defects, and wrong physical properties.

Size and Shape: The reasons for wires being off size or shape have been already given. While every effort is made to draw the wire to the tolerances given, the tolerances themselves may be too great unless the order is accompanied with sufficient information on this point.

Internal Defects: If the steel from which the wire is made contains pipes or seams, these will remain in the wire, but are usually so minute that they cannot be found by any of the ordinary means of inspection. Any slight segregation in the steel will also induce defects in the wire. This segregation causes uneven temper and is also thought to induce, at times, a defect known as "cupping." A "cupped" wire is one whose fracture exhibits the cup and cone form. This defect, it is believed, may also be caused by improper drafting. Such hidden defects are very difficult to detect and frequently can not be found except by actual use of the wire.

Surface Defects: Sometimes complaints are made as to the finish of the wire. If the finish is not satisfactory it may be due to poor cleaning, the fault of the workmen, or to the use of improper coatings. In the case of liquor finished wires, especially, the color may not be of the particular shade desired, or it may vary too much in different bundles. When these features are of special importance to a customer, they should be stated on the order, so that special attention may be given to meeting his requirements in this respect. Other surface defects in wire are scratches, slivers, and seams. Scratches are caused by using a poor die, or they may result from improper lubrication or from pieces of metal or other gritty sub-

stances being drawn into the die with the wire. Slivers, as the name indicates, are sharp pointed projections of metal that rise from the surface of the wire. They may be caused from any one of a great number of conditions, including the ingot and rolling practice. Seams are longitudinal cracks in the surface of the wire and are generally traceable to lack of proper care in rolling. Therefore, in the wire they are very small, and are sometimes very difficult to detect.

Physical Properties: The physical properties of any wire will depend on the chemical composition and quality of the steel as well as upon the exact nature of the drafting practice and of the heat treatment it has undergone. A finished wire taken at random will not be suitable for all purposes, but on the contrary, it will be suited to only a very limited number of uses. If the manufacturer be fully informed both as to the desired properties of the wire and the uses to which the wire is to be put, then he can readily meet the required conditions by determining the composition of the wire and the exact treatment to which it must be subjected. For this purpose it is well to supply the manufacturer with samples from 18 to 24 inches long, of the wire desired, from which, if necessary, physical and chemical tests can be made. A sample of the article made from the wire, showing the manipulation given it by the customer is also always helpful to the mill.

SECTION VIII.

THE HEAT TREATMENT OF WIRE.

The Heat Treating Processes used in the wire industry consist of and are known as annealing, patenting, and hardening and tempering. Of these, patenting may be described as a special toughening process used only in the wire industry, while annealing, hardening, and tempering play such an important role in the industry and the methods of applying these processes have become so highly specialized, that, although they have been thoroughly discussed from the standpoint of general principles and their application to other branches of the steel industry in other chapters of this book, nevertheless, a brief account of their application to the wire industry is highly desirable in this chapter. Therefore, these processes will now be briefly described and discussed in the order of their importance, which is the order in which they were first mentioned above.

Importance and Objects of Annealing: Of the three heat treatments mentioned above, annealing is the most common, and to the soft, or low carbon, steel wires, which constitute by far the largest tonnages, it is practically the only heat treatment given. In general the process is employed in the wire industry to accomplish any one of three objects:

namely, to refine and make uniform the grain structure of rods or wire, to obtain a definite structure in and thus impart special properties to the finished material, and to soften the wire after cold working, i. e., drawing or cold rolling.

Annealing to Refine the Grain: As pointed out in the chapter on the heat treatment of steel, in order to refine the grain of cast or hot worked steel it must be heated above its critical point; and if it is desired to obtain the steel in its softest condition, it must be cooled slowly. This type of annealing, known as true or full annealing, may be used to refine the grain of any steel, but in the wire industry it is chiefly used to remove high or uneven temper in hot rolled rods made from steels of higher carbon content. In such rods the temper of the rods from any particular heat, assuming that the composition of the steel is uniform, will depend upon the grain size and the structural constituents of the steel, which in turn depend upon the finishing temperature of rolling and the rate of cooling. As both of these factors are liable to vary considerably in ordinary practice, not only in different billets or bundles, but also in any given coil, the grain structure and, consequently, the temper will vary accordingly. Now, since uniform temper in the rod is essential to best results in drawing, it is the practice to anneal such rods at a temperature just above the critical range of the steel. Heating to this temperature causes the steel to change to the austenitic state and entirely effaces the original structures. Then, upon slow cooling, the austenite will change back to pearlite, and the grains will be of uniform size. For uniformity, careful regulation of both the temperature to which the steel is heated and the rate of cooling is necessary. After the steel has been heated to its critical point, any further increase of temperature causes a corresponding increase in the grain size. As is well known, rapid cooling, while it gives a fine grain, will harden rather than soften the metal, because it hinders the separation of cementite and thus checks the transformation from austenite to pearlite. The proper temperatures for annealing the higher carbon steels are given in the section on carbon tool steels, while the temperatures for steels of lower carbon content can be estimated from the diagram on page 672 of this book.

Annealing for Definite Structures: This type of annealing is applied to the higher carbon steel wires, i. e., those with a carbon content of .30 per cent. or more, in order to obtain certain definite structures, and is similar to the treatment given carbon tool steels and other high carbon steels in order to make them easy to machine. If a steel in which the pearlite is in lamellar form like that shown in photomicrographs Nos. 3 and 4, Fig. 201 (P. 675), is heated to about 650° C. (1200° F.) and is held at that temperature for a sufficiently long period of time, the iron carbide slowly coalesces, changing from a plate-like form to a granular, globular, or spheroidal, form similar to that shown in photomicrograph No. 3, Fig. 214 (page 776). By properly regulating both the temperature and the time

of the treatment, structures intermediate between these two extremes and best suited to the purpose for which the wire is to be used may be obtained. These structures are sought in high carbon wires mainly to promote or impart free cutting properties. Close regulation of the temperature is imperative in this type of annealing, for in heating the steel to a point so near the critical range a difference of but 25° C. in temperature often means the difference between the globular structure sought and the lamellar structure which it is desired to efface.

Annealing to Soften Hard Drawn Wires: In the previous section, it was pointed out that each successive draft in drawing a wire has a certain hardening effect upon the metal; that the grains become elongated in the direction of drafting; that, if the drafts were repeated successively and often enough, the metal would finally reach a state beyond which the wire would break if subjected to further drafting; and that well before such a condition of brittleness is reached, it is necessary to heat-treat the wire in order to put it in a condition that will permit further drafting without injury. For reasons which have already been stated or will be made apparent in the discussions to follow, high carbon wires are generally patented, while low carbon wires are annealed. Like the annealing of high carbon rods and wire, the annealing of low carbon wires may also be of two types, according to whether the temperature is carried to a point above or to a point below the critical range. In the wire industry these two types of annealing are known as "dead soft" annealing and "process" annealing.

Dead Soft Annealing: If, as is sometimes the case, it is desired to develop maximum softness or ductility in a low carbon hard drawn wire, it is necessary to remove entirely the effects of the previous drawing, and in order to do this it is necessary to heat it above its critical range. As long as the temperature remains below the critical point, the iron remains in the alpha form, and, unless the temperature is at or near the critical point, the energy of the molecules is insufficient to bring about a complete rearrangement of the grains. But when the temperature passes the upper critical point, the iron assumes the gamma form, and a new set of crystals is born, thus totally obliterating the old structure. Then, if the steel cools slowly, the iron changes back to the alpha form, and the crystals also change back to the form peculiar to alpha iron, leaving the structure in its normal, or most natural, condition and entirely free from internal stresses, or strains. In this condition the metal exhibits low tensile strength and gives the highest ductility and softness of which it is capable. Care is required in heating the steel to see that the temperture is not carried too far above the critical point, as this would increase the size of the crystals, which in turn would make the steel weaker and less ductile. The time of annealing should also be regulated so as to make sure that all parts of the charge reaches the temperature required. As to the rate of cooling, this is not of much consequence in the case of

these low carbon steels, but too rapid cooling will have a slight hardening effect. Concerning the use of this type of annealing, it is generally applied to certain classes of finished wire that are to be subjected to severe forming operations, and is seldom, if ever, used to restore drawing properties.

Process Annealing: For wires in process low temperature annealing is employed, hence the term, Process Annealing. This type of annealing is used mainly to restore the ductility of hard drawn low carbon wires, so that they may be drawn to finer sizes, but is also employed to adjust the physical properties of some wires to their uses. To accomplish these results it is not necessary to heat the wire above the critical range, as a temperature between 540° C. (1000° F.) and 650° C. (1200° F.) is sufficient to relieve the strained condition of the grains to such an extent that the material is almost as ductile as it was before any drafting was done upon it. Evidence, both as to the truth of this statement and as to reason why such annealing restores the ductility, may be had by comparing the photomicrographs of Figs. 240 to 243, all from the same wire. Fig. 240 shows the form and arrangement, and, relatively, the size, of the grains in the full annealed steel. In this condition this steel has approximately a tensile strength of 48000 pounds and an elongation in 10 inches of 33 to 34 per cent. Fig. 241 shows the appearance of the structure after a single, relatively light draft. Here, while the size of grains is the same as in Fig. 240, both their form and their arrangement has been changed, being somewhat elongated and apparently forced into parallel rows extending in the direction of the drafting. The steel in this condition would probably give a tensile strength of about 70000 pounds and an elongation of about 5 per cent. From Fig. 242, showing the structure of the wire after it has received a number of drafts, it will be observed that the grains have been crushed and elongated into a "stringer-like" structure bearing little resemblance to their natural structure, which is that of annealed or hot worked steel. This wire would probably give a tensile strength of 140,000 to 150,000 pounds, and an elongation of about 1 per cent. This unnatural form of the grain disturbs the equilibrium of the molecular forces in each grain, so that the molecules have a tendency to rearrange themselves in their natural position, but as long as the steel remains at atmospheric temperatures they lack sufficient energy to do so. But if the steel be heated, the molecular energy is increased as the temperature rises, so that the molecules begin, slowly at first and then more rapidly as the temperature rises to about 500° C., to move into their natural position, thus forming new grains similar to those in the hot worked or annealed steel. The photomicrograph of Fig. 243 shows the relative size, form and arrangement of the grains formed upon annealing the highly strained steel of Fig. 242 at about 590° C. (1100° F.). While certain remnants of the structure produced by drawing still remain, the grains, themselves, are almost normal as to form. In this condition the steel

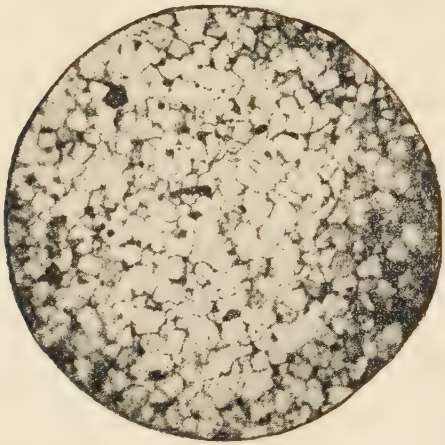


FIG. 240. Structure of .08 to .10 Carbon Steel Rod Annealed, X 100.

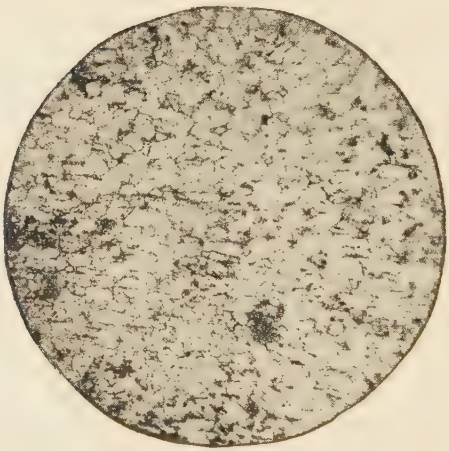


FIG. 241. Structure of .08 to .10 Carbon Steel Wire after One Draft, X 100.

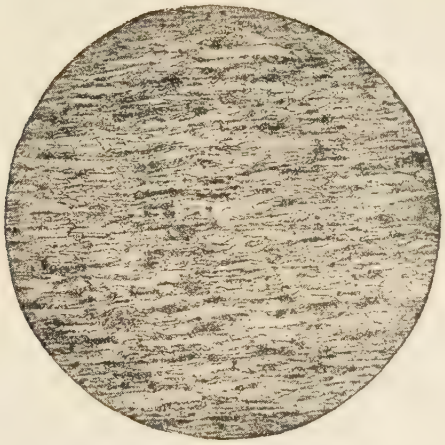


FIG. 242. Structure of .08 to .10 Carbon Steel Hard Drawn Wire, X 100.

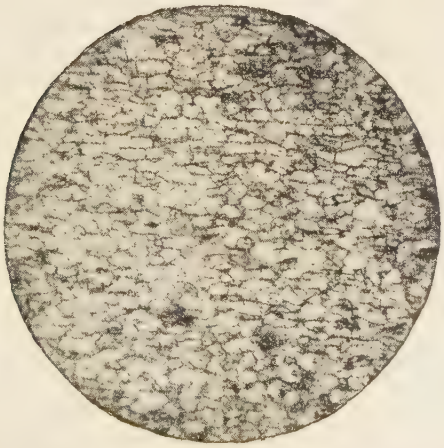


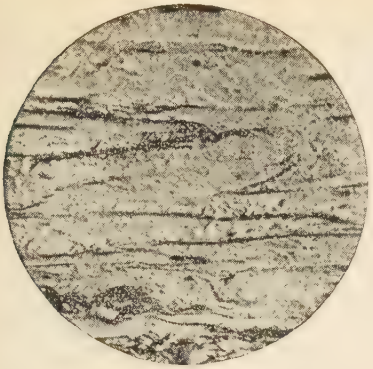
FIG. 243. Structure of .08 to .10 Carbon Steel Wire after Hard Drawing and Annealing, X 100.

will probably give a tensile strength of about 62000 pounds, and an elongation of 28 to 30 per cent. But while this wire is a little stronger and slightly less ductile than if it had been full annealed, it has superior drawing down properties, hence full annealing is seldom applied to process wires.

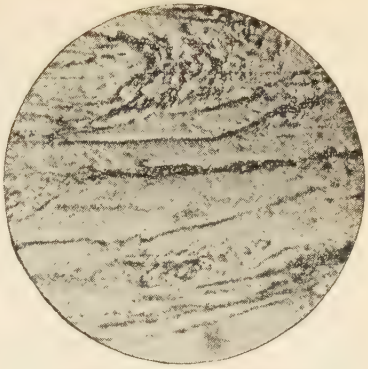
Size of Grains: While the preceding paragraph shows the effect of distorting the grains upon the physical properties, nothing is said about the effect of grain size, and in all annealing, as well as other forms of heat treatment, the matter of grain size is of considerable importance. Large grains weaken the metal, while small grains not only make it stronger but tougher. The reasons for this, as well as the effects of cold working; are to be found in the structure of the grains themselves. According to Rosenhain, Jefferies and other authorities, the grains of alpha ferrite are each made up of small cubical bodies lying face to face and in parallel planes, each cube having a molecule or atom of iron at each corner and one in the center. When the grain is distorted, as in pulling or drawing, these bodies slip upon each other, forming planes of cleavage, or planes of easy slip. Anything that interferes with this slippage will make the metal stronger, while anything that promotes the slippage will weaken it. Small grains offer greater interference to this slippage than large grains, because the planes of cleavage in different grains lie at different angles, and in any one of such small grains the slip cannot progress far before it is stopped by another grain which may offer considerable resistance to the force causing the slip, because the direction of the movement may be greatly changed. In a small section, such as a wire, where the ratio of the diameter of the wire itself to that of the crystals is relatively small, the weakening effect of large grains is likely to be very noticeable. The increase of strength due to drawing may also be explained from the standpoint of slip interference, for, as the grains are distorted, the slip interference becomes greater and greater until most of the grains have been drawn into parallel stringers. In this condition the force required to pull the wire apart should approach the force of attraction of the molecules or atoms themselves, but it never does because some of the crystals begin to break before the others.

The Conditions for Process Annealing involve three factors, namely,—strain, time and temperature. Without strain no change in the crystalline structure takes place below the critical range. As to the effect of the amount of the strain in causing grain growth, or rearrangement, below the critical range, Sauveur[1] has shown that, in the case of steel containing from .04 to .12 per cent. carbon, very slight straining and annealing at 650° C. for 7 hours produce no grain growth, but that moderate straining, such as might be produced by a single light draft, and annealing cause

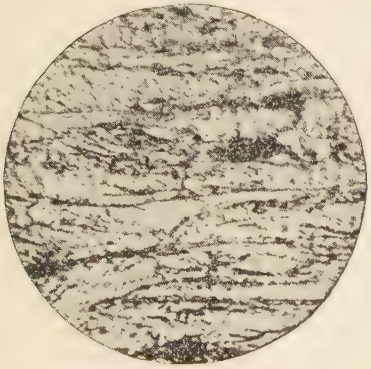
[1]See the Metallography and Heat Treatment of Iron and Steel, 2nd Edition, Pages 265-275.



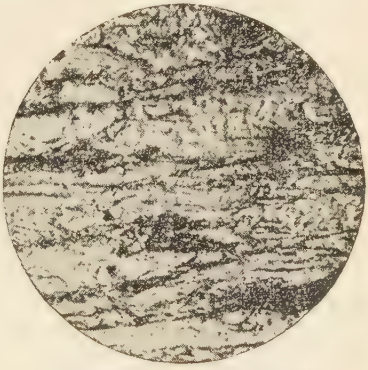
Annealed at 303° C. x 1000



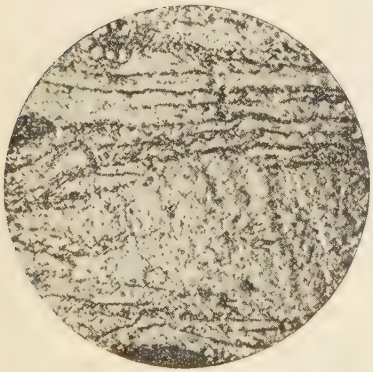
Annealed at 350° C. x 1000



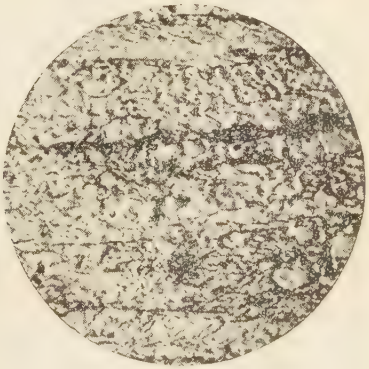
Annealed at 404° C. x 1000



Annealed at 455° C. x 1000

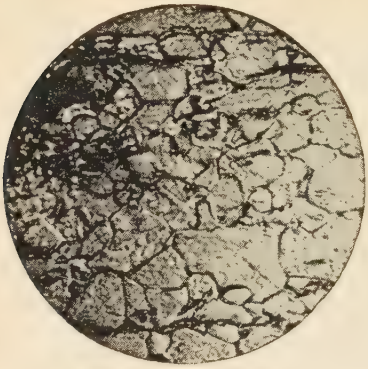


Annealed at 507° C. x 1000

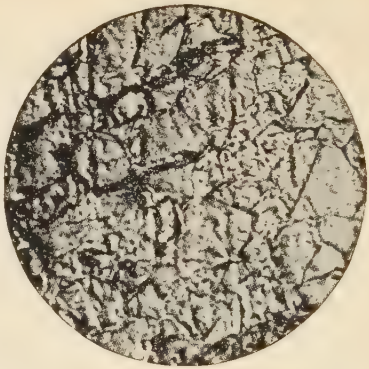


Annealed at 519° C. x 1000

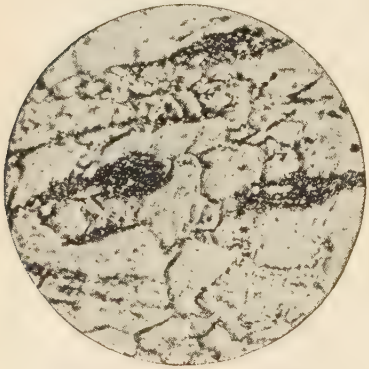
FIG. 244. Series of 10 Photomicrographs showing the changes in the Structure of a hard drawn Wire Annealed at various Low Temperatures.



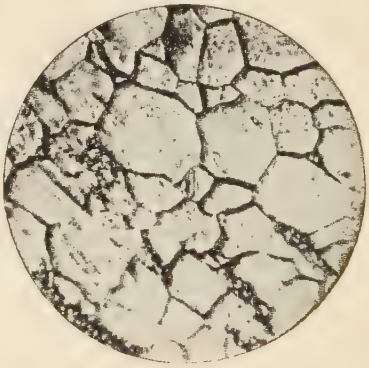
Annealed at 534° C. x 1000



Annealed at 546° C. x 1000



Annealed at 557° C. x 1000



Annealed at 606° C. x 1000

FIG. 244. Series of 10 Photomicrographs of Annealed Wire—Continued.

All this series were made from the same Wire, Diameter of Wire .09 inch. Below 300° C. no change can be observed microscopically. Note the roughened appearance of the elongated ferrite grains annealed at 303° C. to 507° C. This roughening is thought by many to be due to the formation of nuclei for new grains, which are fully developed at 600° C. Others, holding that the drawing breaks the original grains into fragments, think that these crystal fragments, on heating, at first form very small grains, which begin, at about 520° C. to grow rapidly, increasing in size until the transformation point is reached.

the grains to grow to very large size, while over-straining, or severe distortion and annealing at the same temperature and for the same length, of time, produce grains of small size, comparable with the structures shown in Figs. 240 and 243. The condition of strain producing large grains is seldom met with in process annealing wire, because the grains of such wires are usually distorted far beyond that point. When such a condition of strain is present in the wire, the formation of large grains can be avoided by annealing at a lower temperature, or by full annealing. However, when a consumer expects to anneal his wire, this fact should be made known to the manufacturer, when it will be possible, except in a few cases,

to supply the customer with wire that will not form large grains under any annealing conditions that do not involve heating the wire far above the critical range of the steel. In the case of pure, or almost pure iron, and steel containing more than .12 or .15 per cent. carbon, the amount of strain, according to Sauveur, has no effect in producing large grains on annealing, but others have shown that the same tendency persists in .20 to .30-per cent. carbon steel.

Time and Temperature for Annealing: From what has already been said, and the evidence supplied by Fig. 244, it is evident that, for the best results in annealing, careful regulation and adjustment of the time and temperature are necessary. In all types of annealing, sufficient time must be allowed for the whole charge to reach the required temperature, and in low temperature annealing additional time is required for the development of the structure desired. Process annealing requires careful adjustment of time and temperature in order to avoid crystallization, or the formation of large grains, and, at the same time, eliminate the effects of the cold working, because at a low temperature the atoms or molecules move at a slower rate, and more time is required for their adjustment than at higher temperatures. As to temperature, the fact that full control and careful regulation of this factor in all annealing is necessary to satisfactory results cannot be too highly emphasized. If the temperature is carried too high, it invariably gives a coarse grain, especially in full annealing, while if it is too low, it may fail entirely to accomplish the results desired in any type of annealing. In some cases adjustment of the temperature to the size of the wire is also necessary. Fine wire in coils, for example, is generally annealed at as low a temperature as practicable, in order to avoid the sticking of the wire in the coils. After these remarks it is scarcely necessary to say that accurate and carefully standardized pyrometers form an essential part of any equipment for the proper annealing of wire.

Methods of Annealing Wire: While it is possible, theoretically at least, to anneal wire in any kind of outfit in which the proper conditions of time and temperature can be maintained, the efficient handling of the material calls for, and some of the finishes and conditions to be met demand, equipment specially designed for the purpose in mind. These conditions, in general, call for differences in the time of annealing, and differences in the methods of applying the heat, and usually require that the material be protected against oxidation. To meet these conditions, four different methods requiring entirely different apparatus and equipment are used. These are known as muffle annealing, pot annealing, continuous lead annealing and tube annealing.

Muffle Annealing represents the crudest form of annealing used in the wire industry. The common muffle furnace consists of a brick lined chamber about 12 feet long, 8 to 12 feet wide and 2 to 2½ feet high. At the back of the chamber and separated from the muffle proper by a baffle wall is a grate for burning the fuel which heats the furnace. At the opposite

end of the muffle chamber is a hanging door across the whole width of the furnace, through which, when open, the wire is charged and discharged. The bottom of the chamber is provided with a grating of iron rails or castings known as "muffle ladders," the object of which is to form a support for the wire so that the furnace gases will be free to circulate beneath it. The wire is in contact with the open flame, which passes over the fire wall into the muffle proper and then out of the flues to the stack, and it is therefore seriously oxidized. For this reason muffle annealing is generally employed only to meet unusual conditions.

Pot Annealing: This method of annealing is identical in principle with that known as box annealing, the material being placed in a sealed container, or pot, and thus protected from the air and furnace gases during the entire process of annealing. The method is largely used for annealing process steel wire, but considerable copper wire is also pot annealed, for which latter kind of wire a temperature corresponding to a red heat is sufficient.

Equipment for Pot Annealing: A pot annealing equipment consists of pit furnaces, annealing pots and cranes. The pit furnace is constructed of fire brick, and the interior of the furnace should be of a shape and size to correspond with the pots which are to be heated in the furnace. As a rule, the furnace is direct fired with coal, which is burned on a grate at the bottom below the pots, and the flame is conducted into the heating chamber through suitable ports. The construction of pot annealing furnaces varies considerably in detail in different plants, and, like most other annealing equipment, is designed to take advantage of the local conditions of mill and of product. Ordinarily, the furnace construction is such as to protect the pots from the direct action of the flame where it enters the furnace, because an extremely high temperature is detrimental both to the wire and to the life of the pots. A low apron wall of brick is frequently used for this purpose. The annealing pots are cylindrical, pot-like vessels, with an offset at the top to provide space for sealing the cover around the edges. They are made in one piece, of cast iron, or cast steel, or of steel plates formed into shape and welded along the seams. The dimensions of the pots vary widely, depending upon the size of the bundles to be annealed and upon various local requirements. Where bright wire is required, the pots are built with double offset and are provided with two covers which tend to eliminate the oxidizing effect of the air which enters the pots during the cooling operation.

Advantages of Pot Annealing: The chief advantages of pot annealing are the following: The furnace gases are excluded and, if desired, the air may be excluded to such an extent that a bright clean surface may be obtained on the annealed wire. Also, as compared with muffle annealing, pot annealing makes possible a greater uniformity of temperature and a more exact knowledge of the actual temperature, providing a pyrometer is used. Another advantage is that when the wire is cooled in the

pot, the rate of cooling may be comparatively slow, which manner of cooling tends to give a softer annealed product, especially in the case of the high carbon steels. Most of the heavy work in pot-annealing departments may be done with cranes. Also, in pot annealing there is little snarling of wire. With proper appliances, bright annealing is possible, and in general the loss due to scaling is comparatively slight in any pot annealing apparatus, due to the small opportunity for scale formation. The lighter coating of scale also means that less acid is needed for cleaning. Furthermore, sundry finishes may be produced on steel in pot annealing, the results obtained depending largely on how the wire is prepared and how the pot is sealed and cooled. If the air is allowed to come in contact with the wire when it is at high temperature, oxidation will occur, of course. But by controlling the air admitted to the pots, and by retarding the cooling, it is feasible to obtain wire that is black, blue or bright, while liquor finished wire may be annealed white by entirely excluding air.

Continuous Lead Annealing consists merely in drawing the wire through a bath of molten lead heated to the proper temperature. The molten lead is contained in a shallow rectangular steel pan, some 10 to 15 inches deep, 3 to 4 feet wide, and 15 to 25 feet long, the exact dimensions depending upon conditions. Sometimes two pans are used, the first known as the cold pan and the second as the hot pan, and the wire is drawn through each in succession. The pan is heated from below by gases from a coal or gas fire and is supported by a brick setting adapted to the method of heating. In practice several strands of wire are drawn through the bath in parallel. For this purpose the coils of wire to be annealed are placed on free running reels before the annealing furnace, and the wire from each coil is drawn through the bath by means of a take-up block placed at a convenient distance from the other end. For keeping the wires immersed in the molten lead, devices of various forms, and known as sinkers, are used. To obtain bright annealing by this process, it is necessary to cool the wires out of contact with the air. Consequently, when such a finish is desired, the wires from the hot lead bath are conducted directly into long tubes which are kept as nearly sealed as possible.

The Advantages of Lead Annealing are obvious. In addition to protecting the material from the air, the lead not only affords a means of regulating the temperature closely, but also assists in maintaining uniform conditions during annealing operations. The bath of molten metal is readily maintained at a uniform temperature throughout its mass and its temperature can be accurately ascertained at any time by means of a pyrometer. Also, since the process is continuous, it eliminates much handling of the material.

The Principal Use of Lead Annealing is in connection with galvanizing plants, where it is employed to anneal process wire. In these plants lay-outs are provided that permit the wire to be annealed, cooled, cleaned,

washed and dried, or dried and galvanized or tinned, all in one continuous operation. In continuous annealing and cleaning, where the wire is not to be galvanized or tinned, the wire, after passing through the lead bath, is conducted through crushed coal or sand, banked at the end of the lead pan and known as a "Heading." It then passes successively through a water bath, a weak acid bath, a cold water bath, and a hot water bath, thence to the take-up blocks, which are located several yards ahead to permit the wire to dry. This elimination of the customary process of dip-cleaning with cranes is very desirable in the case of process wire.

Tube Annealing is also a continuous process, but instead of a metallic bath, the wire is heated by passing it through hot tubes. The process requires a special type of furnace. This furnace consists of a combustion chamber and a long horizontal heating chamber, in which are arranged arches of special shaped tube bricks provided with holes which form continuous tubes from one end of the furnace to the other. The tube bricks, due to the construction of the furnace, are heated above and below with the hot gases from the fuel, so that the tubes are maintained at a high temperature; and the wire, as it is uninterruptedly drawn through the tubes, is raised to a temperature dependent on the size of the wire, its speed and the temperature of the tubes. Such furnaces may be one, two or three pass furnaces, having one, two or three arches of tube brick.

The Chief Advantage of the tube annealing furnace, as with lead annealing, is that it may be placed in front of the galvanizing or tinning furnace, thus permitting the wire to be annealed and galvanized or tinned in a continuous process, thereby eliminating a handling. By regulating the speed of the wires and the number of passes through the furnace, and by controlling the temperatures accurately, such annealing conditions can be maintained as are required to give the desired properties in the finished wire. The wires are more or less oxidized by this process.

Patenting is a heat treatment applied to rods and wire having a carbon content of .25 per cent. and higher, the term being peculiar to the wire industry. The object of patenting is to obtain a sorbitic structure, which combines high tensile strength with high ductility and imparts to the wire the ability to withstand hard drafting. In the case of process wire, patenting also removes the effect of previous cold drawing.

Methods of Patenting: Patenting is always conducted as a continuous process and consists in first heating the material to a point considerably above the critical temperature, then cooling through the critical temperature at a comparatively rapid rate. In practice, there are three ways of administering the treatment. Thus, the wire may be heated in tubes and be cooled by pulling it from the furnace into the open air, which method is now referred to as "Old Process Patenting." The wire may be heated as before, and be cooled by drawing it into a bath of relatively cold lead, when the process is known as the "Metallic Hardening Process."

The wire can be heated in a bath of very hot lead and cooled in another bath of lead at a lower temperature, as in the "Double Lead Process." In this last process the temperatures of both baths can be controlled nicely and measured accurately, conditions which make it possible to obtain definite structures even in wires of highest carbon content, a feat not easily accomplished in old process patenting. The third method also has the advantage over the other two in that less scale is formed.

The Structure of Patented Wire: As stated above, the object of patenting is to develop a sorbitic structure, and, as explained in another part of this book, this structure represents a step in the transition from austenite to pearlite, in which the grains are very small and the iron carbide is distributed in very finely divided form in the ferrite. (See Fig. 201, page 675, and Fig. 206, page 696.) These two characteristics,—the fineness of the grain and the finely divided state of the iron carbide—distinguish sorbite from pearlite, in which the grains are well defined and the iron carbide and ferrite are highly segregated and occur in a lamellar, or plate-like form. The method for obtaining sorbite described in Part III., Chap. II., consists in heating the steel to a temperature just above the critical range, quenching and drawing back at a temperature of about 600° C. (1112° F.), and it may now be stated that patenting is another method of accomplishing the same result by creating the same conditions in a different manner. The heating above the critical range causes the ferrite, or iron, to change to the gamma form, which dissolves the iron carbide, forming a solid solution, probably of elementary carbon in iron. In slow cooling through the critical range, the iron first changes into the alpha form and recrystallizes. Some of the iron then combines with the carbon to form carbide, and since the iron in this form cannot hold the iron carbide in solution, the iron and iron carbide separate and form in layers within the grains. But when the metal is cooled rapidly through the critical range, as in quenching or patenting, these changes, for lack of time, do not all take place at once, and at the same temperature as before, but at a much lower temperature. Then when the iron changes to the alpha form, due to lack of molecular energy, the iron is unable to form grains, and if the rapid cooling be carried to atmospheric temperatures, as in quenching, the iron may not be able to combine with all the carbon, and any iron carbide formed is entirely unable to segregate. Consequently, the molecules of the latter remain dispersed in the former constituent, giving rise to the very hard and brittle structure known as martensite. Upon reheating this martensite, any uncombined carbon will combine with iron, and the molecular energy is increased so that the molecules are able to rearrange themselves. The metal, therefore, becomes softer and softer as the temperature is increased to 600° C. or 650° C. At this point the iron and iron carbide have become slightly segregated, the latter forming little globules too small to be distinguished with the microscope, but yet large enough to impart a characteristic appearance to the structure, which is

known as sorbite. In this form, the slip interference of the iron carbide is greatly decreased, so the metal is comparatively soft and ductile. But as the grains are very small, the metal is still much stronger, or "tougher," than pearlite. In patenting, the changes that normally take place as the steel cools through the critical range are arrested just as in quenching, but the arresting of the temperature just below the critical range, as in the Metallic Hardening and Double Lead processes, permits the formation of the sorbitic structure at once. After sorbite has once been formed, the rate of cooling will have no effect upon the structure, but too rapid cooling will produce stresses and strains in the material that will have a slight hardening or embrittling effect.

Properties of Patented Wires: The structure obtained by patenting is extremely tough and possesses good drawing-down properties. It is much stronger than the same steel annealed. The patenting process is absolutely necessary to the production of any exceedingly high strength, tough wire, such as music wire. As an illustration, by properly patenting and drawing, a .70 per cent. carbon steel wire is produced having a tensile strength of 375,000 pounds, or over, per square inch. In spite of the great amount of drafting required to raise the tensile strength to this point, such wire will be tough enough to wrap around itself and can be hammered flat to one-half of its original thickness without splitting. Without the patenting process, we would be at a loss to know how to procure wire of this strength which would have anything like the same amount of toughness. It has been possible to make a .85 per cent. carbon steel wire having a tensile strength of 415,000 pounds per square inch, simply by the proper manipulation of the processes of drafting and patenting.

Hardening and Tempering: In other branches of the steel industry, hardening and tempering are usually considered as separate operations, but in wire-making they are more often conducted as a single continuous process, and as hardened wire is always tempered, the two terms are always used together. As in the case of tools and other products of steel, the object in hardening and tempering wire is to control the hardness, or "temper," in order to adapt the material to the use for which it is intended. The process, or processes, is applied to a great variety of wires, such as typewriter wire, umbrella wire, dress-stay wire, curtain spring wire, and wires for measuring tapes, clock and watch springs, door-check springs, etc. Wires for such purposes are generally treated as such, by a continuous process, but in the case of many kinds of springs, tools, and a long list of miscellaneous special products, the treatment is given after the wire has been formed into the article desired, when it is not always possible to use a continuous process for hardening and tempering.

Methods of Hardening and Tempering Wire: For greatest efficiency in hardening and tempering, it is obviously necessary to adapt the method of treatment to the nature of the material and the size and form of the

article. Therefore, on account of the great variety of steels and of articles produced by the wire industry, various methods of treatment involving the use of various kinds of apparatus and of various heating and cooling media, are employed. Thus, for hardening, the material may be heated in muffle, tube or electric furnaces, or in molten lead, and be quenched in water, oil, molten lead, or some other liquid. For drawing the temper, the material may be reheated in open furnaces, in baths of molten lead or hot oil, or by bringing it in contact with hot sand or with hot plates or discs of iron or steel. In continuous hardening and tempering, the heating for hardening may be accomplished in a manner similar to that for patenting, and the quenching by passing it quickly into a tank of water or oil, while for tempering, the material will then be drawn through a suitable bath, such as molten lead, the wire being in continuous motion throughout the process.

Structure and Properties of Hardened and Tempered Wire: The structural changes that take place in hardening and tempering have been mentioned under "patenting," and more fully discussed in a preceding part of this book. Likewise the effect of hardening and tempering upon the physical properties of plain steels may be found in the chapters on heat treatment and fine tool and special steels.

SECTION IX.

PROTECTIVE METALLIC COATINGS.

Kinds of Coatings: Probably more than one-third of all the steel wire drawn is given some kind of metallic coating, either for decorative or protective purposes. This phase of the industry has reached such huge proportions and is of so great importance that a treatise on wire drawing would hardly be complete without at least a brief account of the chief coating processes. As already indicated, considerable tonnages of the medium and larger sizes of wire are given a light coating, or a "liquor finish," varying in color from copper through the various shades of brass to tin, for decorative purposes only, and practically all soft fine wires have to be given this coating for lubricating purposes. This dip metallic coating, which may consist of copper or tin or a combination of the two, is very thin and has but little value as a protection against corrosion. As is well known, all of the common grades of steel will rust sooner or later when exposed to atmospheric conditions unless its surface is covered with some substance that will protect it from moisture and air. To afford such protection, it is the practice to "galvanize" wire, i. e., coat it with zinc, or to "tin" it, or, for certain purposes, to give it a coating of paint, lacquer or japan. While it is also possible to coat steel wire with copper, aluminum, lead, nickel, and the precious metals, these metals are seldom

used for coating wire, except in a few particular cases, so they need not receive any further consideration here. The remainder of this section will, therefore, be devoted to the more important processes known as galvanizing and tinning.

Advantages of Galvanizing: As a protective coating, zinc offers several advantages over other metals. (a) Zinc is electro-positive to iron, which statement means that if the steel of a galvanized wire should be exposed, owing to defective or damaged coating, to corrosive influences, the zinc will first corrode, and its presence will protect the iron from corrosion until after a considerable area has been exposed. Just the opposite reactions might occur with other metals, such as tin, which is electro-negative to iron. The presence of tin under the same conditions would hasten the corrosion of the iron. If the student is not familiar with the terms electro-positive and electro-negative, more information will be found on pages 14, 968 and 984. (b) Zinc may be obtained in a comparatively pure state at a low cost. (c) With zinc, it is easy to obtain a hard smooth coating comparatively resistant to abrasion. (d) The color of the zinc coating is satisfactory for general purposes.

Methods of Galvanizing: There are two methods of galvanizing wire in common use, known as the hot galvanizing process and the electro-galvanizing process, but the latter is used to a limited extent only, because it is more costly than the former and possesses difficulties in addition. In both processes, some 30 wires more or less are arranged side by side and are passed, first, through certain preparatory processes, thence through the galvanizing bath, then, through or over certain forms of "wipes," and, finally, to take-up frames, on which each strand of wire is separately coiled, all these operations being carried on as one continuous process, by attaching the last end of each coil to the first end of the next. As the wires pass through the various baths required to clean and coat them, they are submerged by means of suitable forms of sinkers either of the stationary or rotary type.

Processes Preliminary to Hot Galvanizing: In nearly all cases, wire to be galvanized must be annealed to remove the effects of cold working, and in order to save in handling of the wire, it is common practice to do this work in conjunction with the galvanizing operations by one of the continuous annealing processes. For this purpose either a tube furnace or a hot lead furnace will be built in front of the cleaning and galvanizing apparatus. Since the rate of cooling in process annealing has little effect upon the physical properties of the wire, the wires are cooled in air, or, if the space is limited, low carbon wires will be cooled by conducting them from the annealing furnace into a vat of water. Following the annealing, the next step is cleaning, for which purpose the wire is conducted into a bath of hot dilute muriatic, or hydrochloric, acid. This acid is used instead of sulphuric, which is the acid commonly employed for cleaning in the galvanizing of sheets and tubes, because it acts much more quickly than sulphuric, causes less acid brittleness, and is much more

effective in removing traces of lime remaining from the drawing operations. The iron chloride formed by the action of the acid, as well as any particles of loosely adhering scale must next be removed, and these objects are accomplished by passing the wire through a bath of hot water. While the wire is now perfectly clean, it must also be perfectly dry before it is brought into contact with the molten zinc, but in drying, any exposure to the air, which in practice it is impossible to avoid, results in the formation of a light coat of oxide, or rust. This difficulty is overcome by the use of a flux. In galvanizing sheets, tubes, and some wire products, this flux consists of fused ammonium chloride, commonly known as sal ammoniac, which lies upon the surface of the zinc bath, but for the continuous galvanizing of wire, better results are obtained by passing the cleaned and thoroughly washed wires directly through a dilute solution of zinc chloride and then through a dryer into the molten zinc. The wire thus becomes coated with a thin film of zinc chloride, which tends to protect it from oxidation during the drying and also dissolves any traces of rust that may be formed. It is thought by some that fluxes perform other functions, also, by starting a sort of galvanic action that aids the reaction and alloying of the zinc with the iron, but, if so, the physics and chemistry of this action is not understood.

Apparatus for Hot Galvanizing: From the dryer, the wires are drawn at once into the molten zinc, or spelter, as it is commonly called. This molten metal is contained in a "spelter" pan, which is usually made of boiler plate and is supported by a brick setting of suitable construction for firing with the cheapest and most satisfactory fuel available. The accompanying illustration shows the general form of the pan and the furnace commonly used. The dimensions of these pans are subject to much variation, and depend upon several conditions. Thus, the width will vary according to the number of strands it is desired to galvanize at once, which is usually about 30. The length is dependent upon the size of the wires, the speed of travel, and the thickness of the coating desired. Pans designed for galvanizing coarse sizes of wire may reach a length of thirty feet. The depth of the pan must be sufficient to prevent the wires during a run from coming into contact with the dross which settles to and collects upon the bottom. This dross is an alloy of iron and zinc containing from 3 to 7 per cent. iron, which assumes a paste-like form at the temperature of molten spelter and is very brittle when cold, hence harmful to the coating. As molten zinc oxidizes rapidly, the pan is provided with some form of cover which rests upon the molten spelter and protects it from the air, except at the ends where the wires enter and leave the bath. Here, the surface of the metal must be kept free from oxide by frequent skimming. The mixture of zinc and zinc oxide thus obtained is known as zinc skimmings and together with the dross represent a considerable loss, for the proportion of these waste products to the total zinc

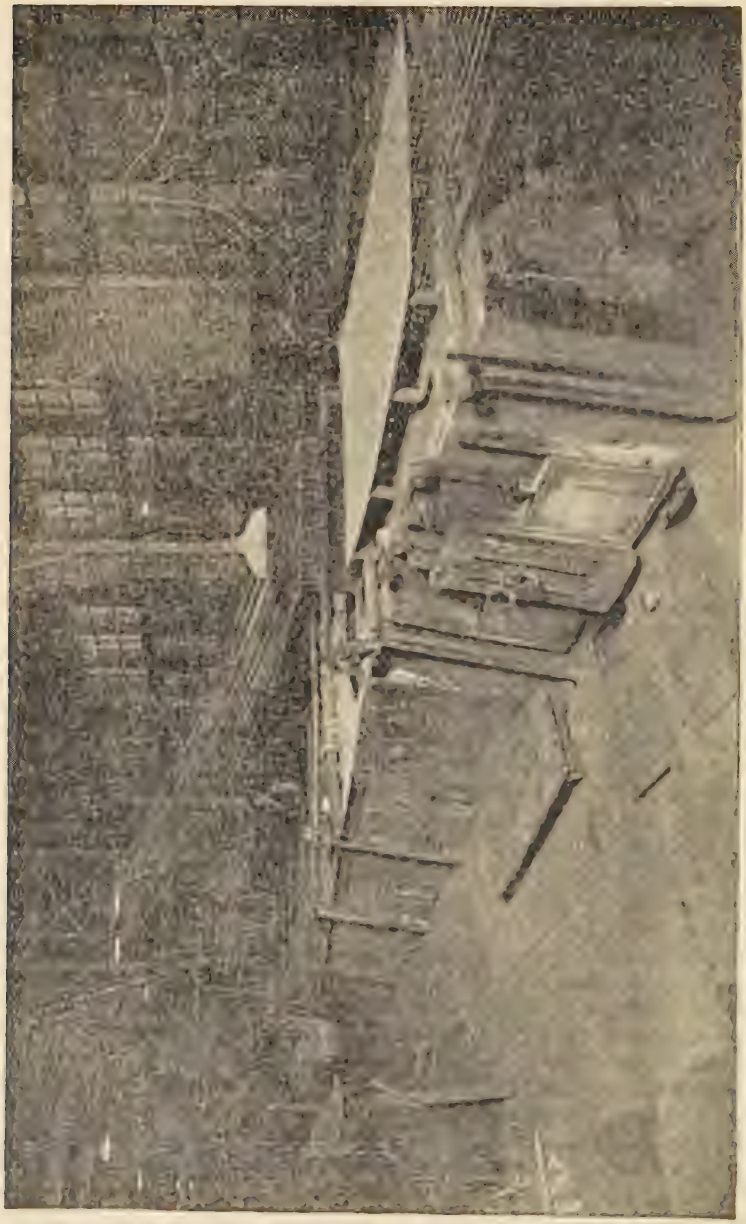


Fig. 245. Hot Galvanizing. Showing the Galvanizing Furnace in the Foreground and the Take-up Blocks in the rear.

used is relatively large, and, although both are refined, the cost of recovering the zinc they contain is relatively large.

Wiping the Wire: As the wires emerge from the galvanizing pan, some of the zinc they carry remains in the molten state for a brief period, and, unless prevented from doing so, tends to flow downward on the surface of each wire, making the coating rough and uneven. Such a coating makes the wire hard to handle, and renders it unsuitable for many purposes, especially where it is to be fabricated by machinery. Besides, such a coating represents an actual waste of zinc, for the durability of an unevenly applied coating is determined by the thinnest part of the coating, not by the thickest parts. It is plain, therefore, that the removal of this excess zinc is a matter not only of economy, but of expediency as well. It is also evident that, in order to form a smooth, evenly distributed coating, the surplus zinc must be removed while it is still in a fluid state. These objects are accomplished by passing the wire, just after it emerges from the zinc bath, through either one of two devices, known as wipes and headers. In the case of wipes, the parts in contact with the wire are made of asbestos, and the type most commonly used is known as the split wipe. It consists essentially of two balls, or moulds, of asbestos fibers held together by some suitable binding material. In service, these two balls are pressed lightly against and about the wire, and are held securely in place by means of cup-shaped holders. The aim in the split wipe is to make it possible for the operators to separate the two halves for the splices to pass, as otherwise the wipe is torn out entirely or badly damaged. Headers are employed for wiping only when extra heavy coatings are desired. A header consists merely of a body of sand, finely broken cinders, or crushed charcoal placed at the exit end of the spelter pan and arranged so that the wires must pass upward through it. In any of these cases, the wipe thus artificially provided, acts as such only for a short time, for a solid hollow cone of spelter soon forms about the wire, either within or in front of the wipe, and this cone of zinc then becomes the real wipe.

Cooling the Coated Wire: After passing the wipes, the coating of the wire is completed, but the manner in which it is cooled should also be given some consideration. If the wire is allowed to cool naturally in the air, the coating, due to the formation of a thin film of zinc oxide on the surface, will be dull and lusterless in appearance, but if the coating is cooled suddenly, as by immersing the wire in cold water, as soon as possible after leaving the wipes, it will have a bright lustrous surface. Now, if rapid cooling does not actually injure the coating by cracking it or making it brittle, cooling it in this manner certainly does it no good. As the real value of the coating as a protection against corrosion depends upon the thickness of the coat and the completeness with which it excludes

moisture from the iron, it is clear that the luster, which is a characteristic of suddenly cooled coatings, is no indication of the quality of the coating, and since this luster can be preserved only for a short time in any natural atmosphere, it is of little value from the standpoint of appearance. Nevertheless, there are still many users of galvanized wire products who attach great importance to the appearance of the coating when it is fresh and, in order to comply with the wishes of these customers, it is necessary to supply them with the bright coating.

Coiling the Wire: As can be seen from the accompanying photograph (Fig. 245), the wire, which, after careful inspection, is delivered to galvanizing department in coils, is drawn through the series of annealing, cleaning and galvanizing apparatus by means of blocks which form it into coiled bundles again. The blocks commonly used for this purpose are of the so-called continuous type, and are similar to a wire-drawing block except that their spindles are mounted in a horizontal position. With these blocks, bundles of wire may be removed at any time without stopping the blocks, and the speed of travel of the wire through the annealing and galvanizing baths are always the same. The form of bundle and the manner of coiling are like that produced on a wire-drawing block, or similar in every respect to a bundle of bright or annealed wire.

Some Features of the Operations for Hot Galvanizing: To the novice the galvanizing of wire may appear to be a simple process. The wires being drawn through the various apparatus and recoiled by the blocks, apparently require little attention from the operator. As a matter of fact, however, the process demands the greatest technical knowledge and skill in order always to obtain the results desired. For example, the firing of such long shallow pans requires not only a properly designed furnace, but constant care and much experience on the part of the operator to keep the temperature of the spelter uniform and constant and to avoid injury to the pan. Similar statements will also apply to the annealing and cleaning equipment. To illustrate further the nature of the knowledge required, we shall discuss briefly some of the factors that determine the quality of the zinc coat.

The Quality of the Zinc Coat, by which is meant its effectiveness in protecting the wire from corrosion and its adaptability to the use to which the wire is to be put, depend upon the completeness with which the zinc covers the iron, the thickness of the coat at its thinnest parts, the uniformity of thickness of the coat, and the physical properties, structure, and chemical composition of the coat. The completeness with which the iron is covered by the zinc depends upon the thoroughness of cleaning and fluxing and also upon the after-treatment of the wire. Attention has already been called to the effects of the manner of cooling the wire as it is leaving the spelter bath. Now, it should be added that the coating may be injured in fabricating the wire. If the cooled wire is bent at sharp

angles or severely deformed by hammering or otherwise, the coating is likely to be cracked or peeled off, especially if it is a heavy one. As to the thickness of the coat and the uniformity with which the spelter is distributed over any given wire, these features depend upon the methods of wiping, the temperature of the molten spelter, and the time of immersion of the wire in the spelter bath. Up to certain limits, the thickness of the spelter coat increases as the temperature increases and as the time of immersion is prolonged. The time of immersion is controlled through the length of the spelter pan and the speed of travel of the wire through the bath. In this connection it should be pointed out that the thickest coat is not always the best, for, as the thickness of the coat increases, its brittleness and its tendency to peel or crack also increases. Some of this brittleness is to be attributed to the fact that zinc, itself, is a comparatively brittle metal. This brittleness could be lessened somewhat by adding other metals, but as these would decrease the resistance of the zinc to corrosion or otherwise affect it adversely, it is the practice to keep the spelter as pure as possible. The composition of the spelter is controlled through chemical analysis, and close limits are fixed for all the impurities it may contain. Other reasons why the brittleness increases with the thickness of the coat are to be found in the fact that the conditions necessary to produce a heavy coat are also likely to affect the structure of the coat itself, for the coat obtained by hot galvanizing is not wholly composed of pure zinc.

The Structure of the Zinc Coat obtained by hot galvanizing under conditions corresponding to a long time immersion is shown by Fig. 246. This is a photomicrograph of part of a cross section of a wire, magnified 250 diameters, that was allowed to remain in a spelter bath until the spelter had solidified. From this photomicrograph it will be seen that the coated wire is made up of four different substances marked A, B, C, and D. Of these "A" represents a small section of the wire, itself, or steel, and "D" is part of the outer layer of spelter, which may be considered pure zinc, although it probably contains a small percentage of

FIG. 246. Photomicrograph Showing Structure of Zinc Coat obtained by Hot Galvanizing. A is the steel base, B and C, alloys of iron and zinc, and D, pure zinc.

iron in solid solution. Layers "B" and "C" are made up of two different alloys of iron and zinc, the existence of which may be explained as follows: Elsewhere in this book it was shown that, when two metals are mixed and heated together, they are likely to form an alloy either with or without the formation of chemical compounds. In the case of iron and carbon, for example, while they may form a solid solution at elevated temperatures, a chemical compound, Fe_3C, forms and separates at certain temperatures, so that carbon steel, in the annealed condition, consists of iron and iron carbide, interspersed. Now, when the steel is brought into contact with the molten spelter bath, an alloying and chemical action takes place, but instead of a single compound, two compounds, having the formulas $FeZn_8$ and $FeZn_7$, are formed. The alloy next to the steel, and designated by B in the photomicrograph, contains the compound $FeZn_8$, while alloy "C," next to the zinc, contains the compound $FeZn_7$. The dark lines showing in the photomicrograph as separating the different areas are not cracks, but are due to variations in the hardness of the different substances, which caused differences in elevation when the specimen was ground and polished.

Electro-Galvanizing: Electro-Galvanizing is the name applied to the process of covering any metal with a coating of zinc by means of an electric current. It is sometimes termed "cold" or "wet" galvanizing to distinguish it from the more common method of hot galvanizing. It is not used very extensively for galvanizing round wires because of the relatively high cost and the high degree of skill required to operate the equipment successfully. However, for galvanizing flat wire and also strip steel, this cold process has certain advantages over hot galvanizing. In galvanizing such materials by the latter process, the edges, especially of strip steel, tend to destroy the wipes, thus making it difficult to secure a smooth uniform coating. The thickness of the zinc coating is readily controlled in electro-galvanizing and depends primarily on two factors, namely, the current density and the time of deposit. By current density is meant the number of amperes per unit of surface of the metal being coated, which is exposed to the electrolyte. The coating, when well applied, adheres firmly to the metal and will stand severe bending without flaking off. But in other respects, the quality of the coat depends upon the condition of the electrolyte, the density of the plating current, the cleanliness of the surface, and on general working conditions.

The Equipment for Electro-Galvanizing consists of a long shallow horizontal vat, known as the plating vat, and is usually made of wood. Attached to one outer side of this vat are the positive bus-bars, or feeders, connected to the plating generator, while on the other side are similar negative feeders. As considerable time is required for suitable electroplating, the vats are made from 50 to 100 feet long in order that the speed of the wires or strips through the vats can be maintained at a reasonable rate for production and still stay submerged in the electrolyte long enough

to receive the desired coating. Since the working voltage is low and the current high, the conductors consist of heavy copper bars. In addition, there are needed a low voltage D. C. generating plant, and means for making and storing fresh electrolyte.

Operation of the Process: The vat is nearly filled with the plating liquid, called the "electrolyte," consisting of a solution of some zinc salt, such as zinc sulphate. This solution must be continually agitated to maintain a uniform density, and it must also be kept clean and at a fairly constant and suitable temperature. For anodes, slabs of zinc are submerged at definite points in the electrolyte and are electrically attached to the positive bus-bars. Alternating with the anodes, are strong copper contact bars which are placed across the vat, immersed a few inches below the surface of the electrolyte, and connected with the negative bus bars outside the vat. These contact bars support the wires being plated, which collectively form the "cathode," and also collect the plating current from the wires. The wires to be electro-galvanized are generally annealed, thoroughly cleaned in acid, then rinsed before they pass through the plating vat, from which the wires pass through or over some simple form of wipe and onto take-up blocks placed far enough away from the wipe to permit the wires to dry in air.

Factors in Controlling the Thickness of the Coat: Theoretically, about 2.5 pounds of zinc can be deposited per hour per 1000 amperes of current. In practice, the amount of zinc deposited will be somewhat less, as no electro-chemical operation can be carried on at 100 per cent. efficiency. The practical maximum current density varies and must be determined experimentally for each set of working conditions. Having determined this and also the efficiency to be expected, it will be possible to calculate the required total current needed to deposit a required amount of zinc in a given time. The current flowing from the zinc anodes through the electrolyte into the cathode wires causes the zinc to dissolve into the solution at the same rate that the zinc is deposited on the wires, so that the solution, if it be continually and correctly agitated, will remain constantly at a uniform density, and only pure zinc will be deposited, although the slabs used will usually contain impurities. As the particles of zinc traveling through the electrolyte actually carry the current, the amount deposited will be directly proportional to the current strength and to the time of current flow. Since the former factor is fixed, the latter must be increased as the required weight of coating becomes greater. This necessity directly reduces the output and, together with the expensive plant needed and the high cost of electric power, limits the more general adoption of this process.

Tests for Galvanized Coatings: The whole galvanizing process is placed in the hands of experienced operators, who keep constant watch over each phase of the process and at frequent intervals make certain

tests to determine the fitness of the material for the purpose for which it is to be used. With respect to the galvanized coatings, these tests are both physical and chemical. The more common of the physical tests are known as the "button test" and the "mandrel test," each being applied to different classes of wire to meet different requirements. In the button test the wire is wound tightly about its own diameter, while in the mandrel test the wire is similarly wound about a smooth mandrel having a diameter that is some multiple of its own diameter. The object in both these tests is to determine if the coating will crack or flake under these conditions and, if so, to what extent. For determining the thickness of the coat and whether or not the zinc has been uniformly distributed, two chemical tests are employed. One of these, called the **lead acetate test,** is a laboratory test used chiefly for determining the exact quantity of zinc per unit of surface galvanized. The other, known as the **Preece** or **copper sulphate test,** though only qualitative, is the best known and most generally used chemical test for galvanized coatings and is the only one found in commercial specifications up to the present time. Specifically, this test, when made under properly standardized conditions, will settle the question as to whether or not the coating is uniform in thickness and whether the thinnest portion will dissolve in a certain solution of copper sulphate in one, two, three, four or more minutes. The terms "one-minute wire," "two-minute wire," etc. are based on this test, and mean that the coating will successfully withstand immersion in a standard neutral copper sulphate solution for one, two, or more minutes.

Method of Carrying Out the Copper Sulphate Test: The standard solution used in the test is prepared by dissolving approximately 36 parts of crystallized commercial copper sulphate in 100 parts of distilled water, adding an excess of pure cupric oxide (CuO), and filtering. The concentration of the solution is then adjusted, by adding water or a stronger solution, so that its specific gravity is exactly 1.186 at 65° F. The samples to be tested are thoroughly cleaned by dipping in benzine or gasoline, rinsing in water, and wiping with clean white cotton waste or cloth, before making the test. A clean test jar, 5 inches high and 2 inches in diameter, is then filled to within one inch of the top with the standard solution at a temperature between 65° F. and 70° F., which temperature must be maintained throughout the test. The sample, or samples, is now immersed in the solution by lowering it endwise into the jar, where it is allowed to remain for exactly one minute, when it is removed, rinsed immediately in water of the same temperature, and wiped until dry with the clean cotton waste or cloth, so as to remove the dark deposit of copper which forms on the surface. These operations are then repeated, the wire being immersed for exactly one minute at each trial, until traces of bright metallic copper begin to appear on the surface of the steel, indicating removal of the zinc, or until the number of one-minute immersions exceeds the number called for by the specifications. In case more than one wire

is tested at the same time, the samples, numbering not more than seven, are immersed simultaneously in the same jar, and these must be kept well separated, though they may be allowed to touch each other at their lower ends. In any case, the lower inch of each sample, being adjacent to the cut exposing the iron, is disregarded in the test. A fresh portion of the standard solution must be used after each complete test of seven wires or less.

Principles of the Test: The principles upon vhich the copper sulphate test depends may be explained as follows: The copper sulphate dissolves both zinc and iron, these two elements displacing the copper in the solution of copper sulphate according to the following reactions:

$$Zn+CuSO4=ZnSO4+Cu.$$
$$Fe+CuSO4=FeSO4+Cu.$$

From these reactions it will be seen that copper is precipitated, or thrown out of solution, in each case. Since the reaction can take place only where the wire is in contact with the solution, this liberated copper is deposited upon the surface of the wire, and the test depends wholly upon the difference in the manner in which this deposit is made upon zinc and upon iron. Now, in the case of zinc, the deposited copper is in a finely divided form, and appears as a black flocculent coating completely covering the wire. As this coating increases in thickness, it tends to shield the wire from the solution, thus retarding the reaction, hence the necessity for removing the wire from the test jar and cleaning its surface at regular intervals of one minute. In the case of iron, however, the copper, if all the conditions of the test are properly observed, is deposited upon the surface in the form of a bright metallic coating which cannot be wiped off and is similar in appearance to that obtained in electroplating. As soon as the zinc has been removed from any part of the surface of the wire, this coating appears on that spot to announce the fact.

Value of the Copper Sulphate Test: As indicated in a previous paragraph, the chief merit of the copper sulphate test is that it reveals any unevenness in the thickness of the coat. However, while the test is not directly quantitative, it also reveals, relatively, the amount of zinc at the thinnest point in the coatings, provided the surface condition, composition and structure of the coatings are the same. And this knowledge is of great importance, for the wearing qualities of the coat depend not only upon the weight of zinc on a given surface, but also upon the evenness with which it is distributed. In service, corrosion begins where the zinc coating first disappears, so that, for a given total weight of zinc applied, the best protection to the steel is offered by the most uniform distribution of this zinc. The test can be quickly made with simple apparatus, and the effect is very apparent, but each phase of the test must be carefully performed under standard conditions to obtain fair comparative results. The latter fact is not generally recognized, the impression being that

almost anyone can make the test without instruction as to the points to be observed. Finally, it should be noted that the copper will plate out upon an alloy of zinc and iron as upon pure iron or steel, but the coat of copper on the former does not adhere firmly to the surface as in the case of the latter and may be brushed off with a fine steel brush.

The Tinning of Wire: Because of the high cost of tin, and of the difficulty of entirely avoiding pin holes in tinning steel wire, only a small amount of steel wire is tinned, and that largely for decorative purposes. As already explained, tin is electro-negative to iron, consequently in the case of steel articles coated with tin the destruction of the steel base will be accelerated when corrosion begins. The tinning process is very similar in principle to the hot galvanizing process and need not be described at length. The wire has to be thoroughly cleaned and fluxed before entering the bath of tin, and as it emerges from this bath it passes through a wipe of wicking wound about the wire, after which it goes to the take-up blocks, either with or without an intermediate water cooling. The tin must be maintained at a fairly constant temperature (500 to 550° F.), for, if too low, the coating will be rough and uneven, and, if too high, it will be discolored, owing to the yellowish tin oxide formed. All copper wire which is to receive an insulation covering of rubber compound has to be tinned to protect the copper from the action of free sulphur present in the insulating material.

SECTION X.

SOME FABRICATED STEEL WIRE PRODUCTS.

Importance of Fabricated Wire Products: Steel wire is worked up into thousands of different kinds of articles, which are used for a great variety of purposes. In a list of such articles will be found many articles of common use, such as automobile and bicycle spokes, hoops, rivets, bolts, chains, buckles, cotterpins, wire netting, wire cloth, and a host of others, each of which consumes large amounts of wire. Since even the briefest description of the fabrication of all these articles would require a great deal of space, we propose here to discuss very briefly only about six of the more important commodities in the fabrication of which great tonnages of steel wire are consumed annually.

Wire Nails: The wire nail has almost entirely displaced the old style cut nail, being better in all respects and much cheaper. A review of any up-to-date nail catalogue will show that there are many varieties as to length, size and style, ranging all the way from the tiniest tack to the long heavy spikes. The common finish on nails is obtained by tumbling, though large quantities are galvanized, tinned, blued by oxidation, or cement coated. In the last named process the nails are given a light

coating of some compound of a resinous nature which greatly increases their holding power.

Nail Machines: All steel wire nails are made in automatic machines. These machines differ greatly in size and in design, but the principle of operation is much the same in all of them and is briefly described as follows: Nails are made on a machine by five distinct operations, namely, 1—Forming the head, 2—Feeding the wire, 3—Pinching the wire, 4—Cutting off the wire and forming the point, 5—Expelling the nail.

The Head of the nail is formed by compressing and flattening, against a die, the portion of the wire which projects beyond this die and remains after the previously formed nail has been cut from the wire. This compressing and flattening is done by a hammer which is attached to a reciprocating member, called a hammer stock, which in turn is actuated usually by a crank and pitman. The amount of wire which projects beyond the die governs the size and thickness of the head and is regulated by adjusting the cutting knives the proper distance from this die. The various shapes of heads are obtained by cutting the proper depression in the die. This die is split, that is, made in two parts, one fixed or stationary and the other movable.

Feeding: After the head is formed, the hammer moves away from the die, and the die opens up and allows the feed mechanism to push the wire with a nail head on the end the correct distance through the die to give a nail of the length required. The feeding mechanism is driven by an adjustable crank on the fly wheel of the machine, and, by adjusting this crank, various lengths of nails can be obtained. This feed mechanism also pulls the wire through a series of staggered rolls, as it leaves the reel, to straighten it.

Pinching: When the hammer has reached the end of the stroke, the wire has been fed the correct amount for the nail required and the die closes to pinch the wire. This pinch is obtained by means of a cam on the crank shaft and a series of levers.

Cutting: Immediately after the wire is pinched, two knives, each attached to a lever, move together and cut the wire. These cutting knives are ground to form also the point on the nail. This point is formed by pressing the wire into the shape required, and, in doing so, some of the metal is squeezed out or protrudes between the knives and is cut off by them. These cut off particles are called whiskers. The cutting levers to which the knives are attached are actuated by various forms of mechanisms deriving their motion from the crank shaft.

Expelling: Sometimes, due to dull knives or not very close adjustment, the nail will still adhere to the wire when the cutting knives open up. The cutting knives open up on the return stroke of the hammer, and, in order to remove this adhering nail, an expeller comes into action, knock-

ing the nail downwards out of the path of the hammer and breaking it off. The hammer on the return stroke forms another head on the wire for the next nail—the wire being pinched during this stroke. The finished nails drop into a pan placed on the floor beneath this mechanism.

Finishing Common Nails: The nails in these pans are collected and placed in a tumbler, care being taken to have nails of only one kind in the tumbler at a time to avoid mixing. Into this tumbler some sawdust is also placed. The tumbler has projections on the inside, causing the nails to be churned when it is rotated. This churning polishes the nails and removes any whiskers which may have adhered to the nail by a thin fin of metal. The sawdust absorbs the grease and oil which the nails collected during their manufacture. The cover of the tumbler has perforations or a screen which allows the whiskers and sawdust to pass through but holds back the nails. After the nails are tumbled sufficiently they are packed in kegs ready for shipment.

Wire Fence: As wood becomes more scarce, an increasing amount of steel wire is used for fence purposes. Today an enormous tonnage of galvanized steel wire is fabricated into woven wire fence and barb wire fence.

Woven Wire Fence: There are a great many types of woven wire fence, varying in style or design, and each may be made up in many different sizes. In a general way, the various styles resemble one another in that they have several "horizontal" or lateral wires which are secured in position with vertical or diagonal "stay" wires, the former being stronger and stiffer than the latter and provided at frequent intervals with "tension curves," or slight loops, to take care of expansion and contraction due to temperature changes. The crossing, or stay wires, with the horizontals, form the meshes, which may be quite large, as in cattle fences, or very small, as in poultry netting, and may be of any one of four forms, namely, triangular, rectangular, hexagonal, or diamond-shaped. They are fastened together, also, in various ways. Thus, in the "continuous stay" fence, the stays are looped about the laterals, while in the "cut stay" fence there is a short piece of stay wire for each space, having its ends twisted about the laterals. The stays may be tied to the horizontals with short tie wires, or they may be electrically welded to them, or the two wires may be woven together. In any case, the work is done by specially constructed and rather complex machines from which the coils of fence will emerge all ready for the market. In the making of these fences, a most rigid system of inspection and tests is maintained, not only in the drawing and galvanizing of the wire, but also in the weaving room, in order to turn out as perfect a product as possible. These same fences made of extra strong wire constitute exceptionally good reinforcement for concrete work. The leading fence manufacturers also produce a line of gates, special fittings, steel posts, and other articles used in fencing.

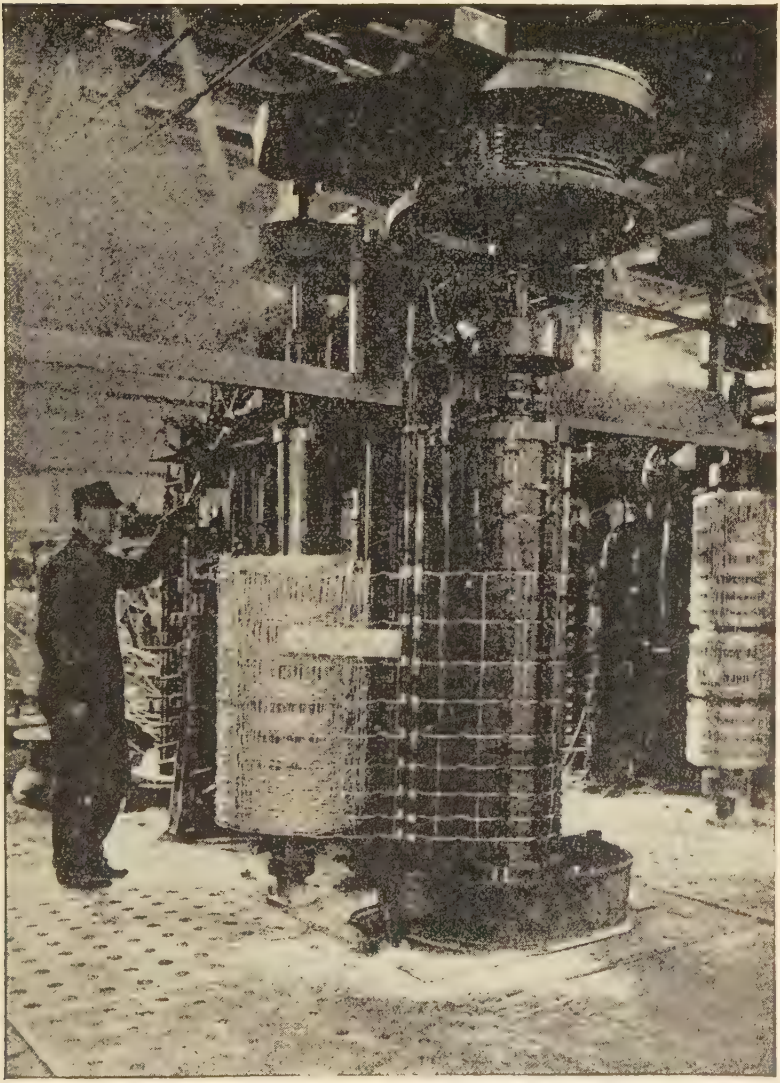


FIG. 247. Making Woven Wire Fence.

Barbed Wire Fence: In this fence, two wires, usually galvanized, and known as line wires, are twisted together, and, at regular and frequent intervals (2 to 6 inches apart) either two or four barbs, which may be round, flat or oval in section, are wound about one or both of these line wires. The barbs are diagonally cut so as to produce a long sharp point extending at right angles to the line wires. Here again we have a great variety of styles and sizes of fence all made by fast-running and rather complex machines. The bulk of barbed wires, however, has the two line wires of No. 12 wire, while the barbs are usually made of No. 14 wire. The fence is furnished to the market in 80-rod, or in "catchweight," spools.

Bale Ties: Large quantities of wire are used annually for tying or bundling bales, bundles, boxes, or packages of every description. While there are several styles of bale ties, each, however, is made of wire that is high in tensile strength and fairly pliable, a goodly percentage of this commodity being made of annealed medium carbon stock having a light oxide finish. The wires are cut to length, and the ends are fabricated to form a means of fastening the two ends together, about five different types of fastener being made to meet different requirements. For tying packages that are fairly uniform in dimensions, both ends of the tie are looped and fastened with a hook. Lengths and sizes vary between wide limits, but most of the tie wires are made of sizes No. 14, 15 or 16. They are put up and sold in bundles of definite numbers varying from 125 to 500 per bundle, the ends of the bundles being burlapped.

Wire Rope: A single solid bar of steel, say one inch in diameter, is very stiff and will stand but little bending before breaking, but if this same bar of steel be worked into a twisted bundle, or "strand," of small wires having the same aggregate sectional area of metal, it will be found to have gained greatly both in flexibility and life, and usually, also, in tensile strength. These reasons account for the large amount of steel strand wire rope that is used as haulage rope, hoisting rope, hawsers, guys, etc., and for such purposes as oil well drilling, ships' rigging, tramways, elevators, and so on. These ropes consist of iron or steel wires ranging in tensile strength from 85,000 to 280,000 pounds per square inch or even more, the wire of very high strength being made from high carbon steel. Wire for ropes used for guy or standing purposes are generally galvanized.

Fabrication of Wire Rope: A full description of the fabrication of wire to form the various types and kinds of rope would make a very lengthy article, indeed, consequently we can cite here only a few of the simplest examples to illustrate a few of the principles involved in steel wire rope making. The first wire rope was made of straight wires held together by fine wires which were wrapped about them at intervals, but this construction was unsatisfactory for obvious reasons. The first great improvement consisted in twisting a number of wires together to form what was called a strand, and then twisting a number of these strands

together to form a rope. At first both the strands and the rope consisted only of wire, and the strands in the rope were few in number, with the result that it lacked flexibility and wearing qualities. But this lack was soon remedied by the introduction of the hemp core, which, together with an increase of the number of strands and the number of wires in a strand, marked the beginning of really successful wire rope manufacture,—from the standpoint of the user, at least. So, a steel wire rope, as it is made today, may be defined as a group of strands, usually in one layer, twisted together helically and symmetrically, with a uniform pitch and direction, around a central core of hemp or wire, each strand in turn consisting of a group of steel wires similarly twisted, in one or more layers, around a central core of wire or hemp. The principle operations of rope making are two in number and are known as "stranding" and "laying."

Stranding: As the name indicates, stranding consists of forming the strands from the wires. This work is done on a special machine too complicated to be described here. It is sufficient to say that the stranding machine is so arranged that it will twist at one time from 7 to 37 wires into strands of the desired construction, and made up of several layers of wires, with equal tension on all the wires and without torsion on any of the individual wires; and by putting a strand of 37 wires through the machine repeatedly, additional layers of wires may be twisted about it, forming a strand of 61, 91 or 127 wires or more if desired. As the wires are being twisted into strands, they are carefully and evenly lubricated. As just indicated, the strands may vary in construction. The simplest in form is that known as the "concentric strand." In this strand a central wire is surrounded with a layer of six wires, and this layer with additional layers of 12, 18, 24, 30 or more wires, according to the size and type of rope required, all wound in the same direction. Many modifications of this simple construction are obtained by using different sizes and groupings of wire, twisting each layer in different directions, substituting hemp for the wire core, and so on, each style having its own particular advantage.

Laying: The final operation in wire rope making is called laying. It consists in assembling the strands and twisting them into the finished rope, and is similar to stranding, except that the machine is much larger and the strands are fewer in number than the wires in stranding. In most cases the strands are laid about a hemp core, but a wire center is required for some purposes. The center made of a fibrous material is needed for flexibility, long life, and lubricating purposes, it being saturated with some suitable lubricating compound.

There are several types of lay, the first and most used type being the "Regular" lay, in which the strands of the rope are laid in the opposite direction to that of the wires in the strand. The "Lang" lay rope is one in which the wires in the strand and the strands in the rope are all twisted in the same direction. All flattened strand ropes are "Lang" lay. In a

Standard Hoisting Rope—Regular Lay
6 Strands—19 Wires to the Strand—1 Hemp Core

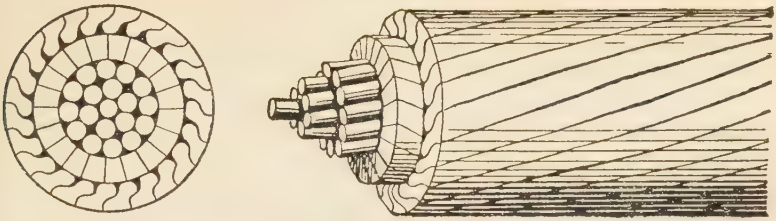
Transmission, Haulage or Standing Rope—Regular Lay
6 Strands—7 Wires to the Strand—1 Hemp Core

Transmission, Haulage or Standing Rope—Lang Lay
6 Strands—7 Wires to the Strand—1 Hemp Core

Fig. 248. Showing different types of Wire Rope.

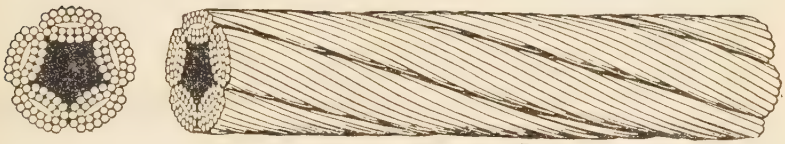
"Reverse" lay rope, half the strands are regular and the other half, "Lang" lay. The object of "Lang's" lay is to secure a greater surface of steel to withstand abrasion, while a "Regular" lay gives a balanced construction. Another construction, which gives a non-spinning rope, is made up of six strands of "Lang" lay around a hemp center, surrounded by twelve strands of "Regular" lay, laid up in reverse direction, all strands consisting of seven wires.

Types of Wire Rope: By changing the kind of centers, or the kind or number of strands or manner of laying them up, it is possible, as can be seen from the accompanying illustration (Fig. 248), to secure a great variety of combinations, each representing a particular type or style of rope best suited for some particular purpose. In general, stiffness and tensile strength and surface wearing quality increase with the carbon content of the wire and with the size of individual wires, while, conversely, flexibility is secured by increasing the number of wires in the strand, or the number of strands in the rope or both. In the construction of a high grade steel rope, only the best of materials can be used; much skill, knowledge and experience are required; and all the processes from the steel mill to the laying machine have to be watched and controlled with extreme care and accuracy.

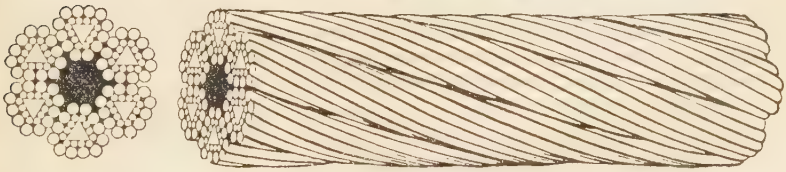


LOCKED COIL TRACK CABLE

NON-SPINNING HOISTING ROPE
18 Strands—7 Wires to the Strand—1 Hemp Core



FLATTENED STRAND HOISTING ROPE
Type A—5 Strands—28 Wires to the Strand—1 Hemp Core



FLATTENED STRAND HOISTING ROPE
Type B—6 Strands—25 Wires to the Strand—1 Hemp Core

FIG. 248. Showing different types of Wire Rope—Continued.

Wire Springs: As in the case of wire rope, there is a great diversity in styles, kinds, shapes, and sizes of springs, ranging from the delicate hair spring of the watch to the substantial buffer, or draw-bar, spring on the Pullman car, or the large, flat, coiled, motor spring. All springs, except some of the cheaper grades of furniture springs, are drawn and formed from medium or high carbon stock, the wires being either hard drawn or tempered and blued, but as to shape they may be round, flat or rectangular in section. The following classification includes all springs in common use:

1. **Compression Springs;** These springs are wound with greater or less space between adjacent coils and are provided with plain or ground ends. They are furnished in a wide range of sizes and strengths to meet sundry conditions.

2. **Extension Springs;** Generally, extension springs are close wound, usually with a considerable amount of initial tension, and, as they are used to resist pulling forces, they are provided with hook- or loop-ends.

3. **Helical Springs;** The term helical springs is a trade name for extension springs used in great volume by manufacturers of spring beds and couches.

Strength of Spiral Springs: Either of the three foregoing types of spiral springs may be strengthened by increasing the size of the wire, or by decreasing the mean diameter of the helix, but the strength of the spring will be no greater than that of any single coil. The total travel of a spring to obtain its load capacity depends upon the number of coils, and increases with the number in the spring.

4. **Torsion Springs;** A torsion spring is one in which work is required to wind up the spring about its own axis,—never to unwind it. The ends may be finished in several ways. Thus, they may be bent in radially towards the center of the coil, outwardly directly away from the center, or upward and downward.

5. **Upholstery Springs;** These are used to serve as cushion or bed springs. They are made in two styles, known as full-springs and half-springs, and, in either, one or both ends may be "knotted," that is, twisted about the wire at the beginning of the second coil.

6. **Clock and Motor Flat Springs;** These springs are made of cold rolled high carbon strip steel, of proper width and thickness to meet specifications, and are tempered and polished, or tempered, polished and colored. The ends are punched as desired, and the coils are wound spirally and held in compact shape by a retaining clip consisting of a two-thirds ring of steel sufficiently strong for the purpose. These springs are produced in a multiplicity of sizes for different purposes.

7. **Jig Springs,** and **Specially Formed Wires;** These represent a group covering an endless variety of odd shapes and sizes, made or formed in jigs or with small hand tools. These springs, as a rule are used to serve as more or less simple parts of mechanisms.

The Elliptical Springs: Elliptical springs are generally used on wagons, automobiles, etc. They are not included in the foregoing list for the reason that this style of spring has grown into an industry by itself and differs materially in principle from the other forms of coiled springs.

CHAPTER III.

THE MANUFACTURE OF SHEET MILL PRODUCTS.

SECTION I.

CLASSIFICATION AND STEPS IN THE MANUFACTURE OF SHEET STEEL PRODUCTS.

Sizes of Sheets and Plates: So far as linear dimensions are concerned, there is no sharp line of distinction between sheets and plates, as they over-lap to a considerable extent. There is a government ruling to the effect that the thickness of a sheet, to be classed as such, shall not exceed the equivalent of No. 10 U. S. S. Gage, 5.625 lb. per square foot, or approximately $\frac{9}{64}$ inch. As to other dimensions, sheets seldom exceed 54 inches in width and 180 inches in length. As a rule, $\frac{3}{16}$ inch is about the thinnest plate that can be profitably rolled on the ordinary heavy plate mill. The lightest plates regularly rolled by the Carnegie Steel Company are $\frac{1}{4}$ inch thick, approximately 10 pounds per square foot, and these may have a maximum width of 132 inches, though plates as thin as $\frac{5}{64}$ inch can be rolled on lighter mills. In the range between $\frac{1}{4}$ inch and $\frac{5}{64}$ inch in thickness are products that may be classed as light plates, or, as is the custom in some localities, jobbing sheets. These products are rolled from slabs on light plate mills, sometimes composed of a two-high roughing stand and a three-high finishing stand of the Lauth type. The thicknesses of these plates or sheets are usually controlled by rolling slabs of given weights out to given widths and lengths, though the heavier ones are sometimes calipered. On account of their lightness, these plates cool so rapidly that it is seldom possible to finish them at temperatures above the critical range. Hence, they must be annealed before they can be used for any purpose involving bending or other severe distortion of the material.

More Vital Distinction Between Sheets and Plates: But while the difference between plates and sheets is marked by no sharp line in sizes, there is a vast difference in the methods of manufacturing them. This difference is due in part to the difference in uses to which the two classes of material are put, and in part to the inherent difficulties of rolling the thinner material. In the uses to which plates are put, utility is the prime consideration, hence very little regard to their appearance is required aside from the elimination of such surface defects as might impair their strength and ductility. As explained in a previous chapter, they are rolled one at a time from slabs heated to almost a white heat, on a comparatively simple mill, and as their thickness causes them to retain heat well, the

rolling can be completed while they are yet red hot. The coating of oxide which forms during the rolling is disregarded, and the plate is put in service about as it comes from the mill, so far as surface conditions are concerned. Sheets, on the other hand, are put to uses in which both utility and appearance are important, and frequently to uses in which their utility largely depends upon the condition of their surfaces and their exactness as to gage, as well as such physical properties as ductility and strength. They are rolled from sheet bars, flat bars eight inches wide, of various weights and lengths that correspond respectively to the gages and lengths and to the widths of the sheets. These bars are first heated, then passed sidewise through a two-high stand of flat plain rolls until they have been reduced in thickness a certain amount and are no longer hot enough to roll. In the case of sheets lighter than about 16 gage, these roughed-down bars are then re-heated and rolled again until they have been reduced in thickness to the gage desired. As the thickness of sheets lighter than 12 gage makes it difficult, even impossible in most cases, to finish the rolling by working one sheet at a time, the roughed out sheets are matched in twos for No. 18 and heavier, and in threes or fours for lighter gages. Then by rerolling, or by a series of operations, consisting of re-heating and rolling, accompanied by doubling for the lighter gages, they are finally rolled to the gage desired in packs of from two to eight, rarely sixteen, sheets each. The sheets are then subjected to various finishing processes designed to impart the finish and physical properties required by the uses to which they are to be put.

Wide Use of Sheets: As these uses differ widely and are numerous, too, the sheet steel industry is an industry of specialties. The truth of this statement is more fully appreciated by a glance at a list of these uses. Thus, one finds that sheets are used in the manufacture of agricultural implements, automobiles and armatures; of buggies, barrels and boats; of ceilings, culverts and caskets; of fence posts, furniture and flumes; of pans, pens and passenger cars; of radiators, roofing and rain gages; of ships, shovels and stoves; of tacks, tanks, tea trays, toys and tubs; and so on through the alphabet to washing machines, well-casing and wheels.

Classification of Mills: From a manufacturing point of view, all sheet steel products are put in three divisions, namely, jobbing mill products, sheet mill products, and tin mill products. While in general, jobbing mills are larger and heavier than sheet mills, and sheet mills larger and heavier than tin mills, there can be no sharp line of division drawn, based on sizes, for they overlap to a great extent, just as plates and sheets.

Plate and Jobbing Mills: Heretofore, the limits included in any classification of plates and sheets have been largely influenced by the equipment of the plant or plants under consideration; but practice, through wider experience, is approaching a standard, and class lines of products are becoming better defined. As an example of a recent large-scale installa-

tion, the Gary Sheet Mills of the American Sheet and Tin Plate Company may be cited. This plant is divided into three operating departments, namely, a sheet department, a jobbing department, and a plate department. The two latter departments operate two 84-inch plate mills, finishing plates to a maximum width of 72 inches, and four jobbing mills capable of finishing sheets up to 60 inches in width. Each of the plate mills consists of a two-high reversing stand of rolls for roughing and a three-high Lauth mill for finishing, both individually driven with electric motors, and set up in tandem. The rolls in both stands are kept cold with water sprays. They roll from slabs, and on one heat, plates from ¼ inch in thickness to No. 12 gage, inclusive. The jobbing mills, each of which consists of a non-reversing two-high roughing and a two-high finishing stand in train, roll jobbing sheets from 13 gage to 16 gage, inclusive, all from sheet bars. These bars, heated just to the scaling temperature, are broken down singly in pairs on the roughing stand, then matched, that is, placed one upon the other, and finished in the next stand without reheating. The roughing rolls are sprayed with water to keep them cool, but the finishing rolls are run hot. Both the plate mills and jobbing mills are equipped with annealing furnaces, through which the materials must pass on their way to the levelling or flattening rolls, cooling tables, and shears. With this equipment in mind, the classifications shown in the following table are most logical and correct.

Table 98. Classification of and Approximate Range of Sizes Rolled on Plate, Sheet and Tin Mills of the Constituent Companies of the United States Steel Corporation.

CLASSIFICATION OF MILLS AND PRODUCTS	ROLLING RANGE		
	Length	Width	Thickness
Plate Mills { Universal	20 to 80 ft.	12 to 48 in.	¼ in. to 2½ in.
Plate Mills { Sheared	10 to 60 ft.	48 to 152 in.	¼ in. to 2¼ in.
Jobbing Mills { Light Plate	8 to 20 ft.	36 to 72 in.	3 gage (¼″) to 12 gage (7/64″)
Jobbing Mills { Heavy Sheets	7 to 15 ft.	24 to 60 in.	10 gage to 16 gage
Sheet Mills	5 to 13 ft.	20 to 48 in.	10 gage to 30 gage
Tin Mills	4 to 8 ft.	16 to 36 in.	14 gage to 38 gage

The ranges in gages require a few words of explanation. In each case the gages given represent the approximate maximum and minimum, and it is apparent that the heaviest and the lighter gages can not be made in the largest sizes. The greater portion of the work done on sheet mills is from 18 to 30 gage, and that on tin mills 28 to 38 gage. Anything lighter

than 30 gage is considered light for sheet mills, and anything heavier than 20 gage is heavy for tin mills. Whether the sheet and tin mills can roll the heavier gages depends on the length, for, as will be seen later, there are limits as to the size of bar each can handle.

Classification of Sheet Steel Products: The great diversity of uses to which sheets are put, and the various modifications in treatment during the processes of manufacture required to adapt them to these uses, make a comprehensive classification of the sheet steel products, whether based upon uses or processes of manufacture, somewhat difficult. The following classification of the chief sheet steel products has been attempted in the hope that it may serve as a guide for the logical study of the subject. The terms employed in the table are those commonly used by the trade in designating these products.

Table 99. Sheet- and Tin-Mill Products.

A. Sheet Mill Products.

I. Black Sheets.

1. Armature Sheets.
2. Automobile Body Sheets.
3. Automobile Crown Fender Sheets.
4. Automobile Fender and Hood Sheets.
5. Automobile Frame Sheets.
6. Automobile Radiator Casing Sheets.
7. Automobile Wheel Sheets.
8. Blue Annealed Sheets.
9. Blued Elbow Sheets.
10. Blued Stove Pipe Sheets.
11. Ceiling Sheets.
12. Drum Sheets.
13. Dynamo Sheets.
14. Enameling Sheets (for vitreous enameling).
15. Full Cold Rolled Blued Sheets.
16. Full Cold Rolled, Reannealed Sheets.
17. Full Pickled, Full Cold Rolled, Reannealed Sheets.
18. Furniture Sheets.
19. Galvanizing Sheets.
20. Lath Sheets.
21. Locker Sheets.
22. Nickel Plating Sheets.
23. One Pass Cold Rolled, Box Annealed Sheets.
24. Pickled, Cold Rolled, Reannealed Sheets.
25. Pickled Locker Sheets.
26. Pole and Rotor Sheets.
27. Polished Blued Sheets.
28. Range Sheets.

Table 99. Sheet- and Tin-Mill Products.—Continued.

A. Sheet Mill Products.

I. Black Sheets.
- 29. Scraper Plates.
- 30. Single Pickled Sheets.
- 31. Shovel Sheets.
- 32. Tack Plate.
- 33. Tank Sheets.
- 34. Transformer Sheets.

II. Formed Black Sheets.
- 1. Corrugated Sheets, straight and curved.
- 2. Other Roofing, Siding, &c.

III. Coated Sheets.

i. Galvanized Sheets.

a. Flat Galvanized Sheets.
- 1. Standard Sheets.
- 2. Heavily Coated Sheets.
- 3. Tight Coated Sheets.
- 4. Culvert Sheets.
- 5. Flume Sheets.
- 6. Ice Can Sheets.

b. Formed Galvanized Sheets.
- 1. Corrugated Sheets, straight and curved.
- 2. Other Roofing, Siding, &c.

ii. Long Terne Sheets.
- 1. Bright Finish.
- 2. Oil Finish.

B. Tin Mill Products.

I. Black Plate.
- 1. Annealed Sheets (or Plates).
- 2. Annealed, Cold Rolled Sheets (or Plates).
- 3. Blued Elbow Sheets.
- 4. Blued Stove Pipe Sheets.
- 5. Ceiling Sheets.
- 6. Cold Rolled Annealed Sheets (or Plates).
- 7. Enameling Sheets.
- 8. Full Cold Rolled, Blued Sheets.
- 9. Full Cold Rolled, Reannealed Sheets.
- 10. Full Finish Sheets.
- 11. Galvanizing Sheets.
- 12. Milk Can Sheets.
- 13. Nickel Plating Sheets.
- 14. Pickled, Annealed Sheets (or Plates)
- 15. Polished, Blued Sheets.
- 16. Show Card Sheets.
- 17. Tea Tray Sheets.
- 18. Unannealed Sheets (or Plates)

Table 99. Sheet- and Tin-Mill Products.—Continued.

B. Tin Mill Products.
- II. Coated Plate.
  - a. Tin Plate.
    1. Standard Cokes.
    2. Best Cokes.
    3. Kanners Special Cokes.
    4. Charcoals: A, 2A, 3A, 4A, 5A, Premier, or similar brands.
  - b. Terne Plate.

    8-, 12-, 15-, 20-, 25-, 30-, 32-, 35-, 40-lb. coatings.
    1. Bright Finish.
    2. Oil Finish.
    3. Greasy Streaky Finish.
    4. Pure Palm Oil Process.

Sheet Mill Operations and Processes: While this list gives most of the common sheet and tin mill products, it gives no hint of the great number of operations or of the amount of work required to produce them. For this reason, and also to indicate the sequence of hot mill operations and processes, the following table, or outline, is prepared. No sequence of finishing operations that will hold for all cases can be given, for the number of processes, as well as the order of applying them, are varied greatly according to the use to which the sheets are to be put. In studying this table, it must be kept in mind that no one sheet will pass through all these operations, as the treatment varies with the kind of sheet, the grade and the gage. Many of the operations are common to all sheet products and these are set out next to the margin, while operations less generally used are indented:

Table 100. Sheet and Tin Plate Mill Operations and Processes.

A. Hot Mill Operations—Sheet and Tin Plate.

Shearing the Bar.
- Pickling the Bar.

Heating the Bars—Pair Furnace.

Roughing or breaking down the Pairs.

Opening the break-down.
- Pickling the break-down.

Matching.
- Doubling.

Heating the break-down.

Rolling the break-down, "Running-over," or finishing.
- Opening the run-over.
- Doubling the run-over.
- Heating the run-over.
- Rolling the run-over—finishing.

Shearing the sheet or pack.
- Opening the pack.

Table 100. Sheet and Tin Plate Mill, Etc.—Continued.

B. Finishing Operations for Black Sheets and Plates.

- Cold Rolling
  - Pickling.
    - Black.
    - White.
    - Scouring and drying.
  - Annealing.
  - Open or Blue Annealing.
  - Box Annealing.
    - Full or Black Annealing.
    - Light or White Annealing.
  - Levelling.
  - Roller Levelling.
  - Stretcher Levelling.

C. Coating Operations.

- Sheet Mill Products.
  - Galvanizing.
  - Terne Coating—Long ternes only.
  - Painting.
  - Blueing and Polishing.
- Tin Mill Products.
  - Tinning.
  - Terne Coating—Short ternes.

D. Forming Operations.

- Corrugating, crimping, stamping, punching, curving.

E. Inspecting or Assorting.

- Testing.
- Reckoning.
- Packing.

Plan of Study: The carrying on of all these operations requires an immense amount of equipment, and the employment of great numbers of highly trained specialists. For many and varied reasons, no one plant is equipped to carry out all the operations, nor able to produce all the different varieties of sheet steel products. Therefore, the plants themselves are more or less specialized, each having an equipment best suited, and a personnel especially trained, to produce certain products only. It seems best, therefore, to present this subject, under the two heads of Sheet and Tin Plate, as a general discussion of the construction and operation of sheet and tin plate mills, describing the different operations and their effects in the order outlined above.

SECTION II.

THE SHEET BAR.

Kinds of Steel Used for Sheets: Sheets are now made from various kinds and grades of steel. The steel used is ordered to specifications best adapted to the purpose for which the sheet is intended. Since most sheets are subjected to severe distortion in forming for service, the carbon content is usually low, below .12 per cent., though for certain articles, like shovels and other tools, a carbon content as high as .75 per cent. may be used. To prevent the sheets from sticking together in the pack, the presence of a certain amount of phosphorus or silicon is very desirable. To be effective for this purpose the former element should be present to the extent of .04 per cent. and the latter to the extent of .03 to .06 per cent. In the absence of these proportions of these elements, special precautions in hot rolling, entailing additional labor and other expense, are necessary to prevent the sheets from being welded together. In acid Bessemer and acid open hearth steels, the requisite amount of phosphorus is present naturally in the steel. On account of the larger amount of scrap used in the acid open hearth, the phosphorus content of steel made by this process can be kept, and is on an average, somewhat lower than in the acid Bessemer. Steel made by the former process usually contains from .040 to .075 per cent., and that made by the latter, .080 to .100 per cent. In basic steel, which is naturally low in phosphorus, the amount of this element is regulated by additions of ferro-phosphorus to the steel in the ladle and is kept between .04 and .06 per cent. For the most ductile sheets, basic steel is used without the addition of the ferro-phosphorus. Few alloying elements are called for in steel used for sheets. Silicon, in relatively large amounts, is added to steel for electrical sheets. These sheets are used in building up the laminated cores of transformers, electro magnets and armatures, because the silicon reduces the magnetic hysteresis and increases the permeability of the steel, thus decreasing the loss of electrical energy known as iron loss. In these sheets the manganese content must be low, else the sheets will be somewhat brittle. As noted elsewhere, copper is added to either Bessemer or open hearth steels for the purpose of inhibiting corrosion of the sheets in service. The copper content usually specified is .15 to .25 per cent.

Determining the Size of Bar to Be Used: The steel from the steel works is generally delivered to the sheet mills in flat bars 8 inches wide and approximately 30 feet long. The thicknesses of these bars, which vary according to the gage and the length of sheet to be made from them, are expressed in pounds per linear foot, and range from 8 to 60 pounds. In the case of a mill handling small orders, it will be evident from what follows that a supply of all the sizes, from 8 pounds up, and of all grades must be kept in stock. As a first step in the rolling of the sheets, these bars are carefully inspected as they are being unloaded from the cars, after which

they must be cut into lengths corresponding to the width of the sheet to be made, with an allowance of from ⅞ inch to 1¼ inches for scrap, depending upon with what allowance the bar can be cut to best advantage. The weight of the bar to be used is found by a very simple arithmetical calculation from the given length and gage of the sheet to be rolled. But it is not always possible to match the calculated weight of the bar required by the sheet exactly with the actual weight of the bar, for two main reasons. First, except in the case of very large orders or certain standard products, it is impracticable to attempt to roll the sheet bar to order and exact weight, but these bars must be stocked in certain standard weights. Second, it is practically impossible, even with the most modern equipment, to roll the bar itself exactly to weight, and a certain tolerance either over or under in the weight, or both, must be allowed. The bar to be used, therefore, becomes a matter of selecting one nearest the weight desired and within certain fixed limits, or tolerances. Furthermore, it will be apparent from the description to follow that a certain amount, which must be estimated from practice, must be allowed for scrap or waste. This allowance varies in different mills, and cannot be predetermined with exactness.

Shearing the Bar: Many different types and kinds of shears are in use, hence a description of sheet bar shears cannot be undertaken. Suffice

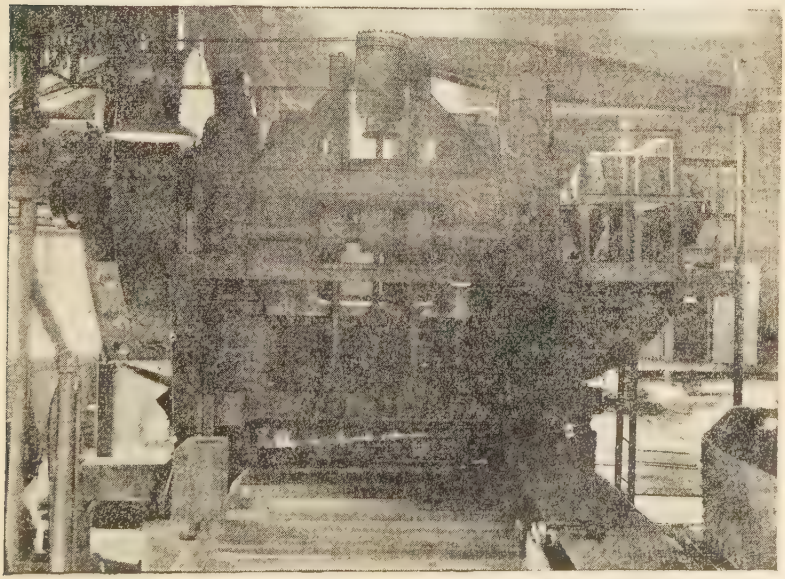


FIG. 249. View of Bar Shears. Entering End. Capacity, Eight 2½-Inch Bars.

it to say, they must be strong and well built, with a stroke of two inches or more, for the heaviest sheet bar has a thickness of a little more than one and one-half inches. In the new and modern plants the shears are made capable of cutting two to eight bars of medium weight at once. They are provided with a live roll delivery table in the rear and a length-gage stop in front, and some are equipped with automatic devices that place the sheared bars in piles upon stands or boxes ready to be moved by crane or truck to the hot mills. As the bars are being sheared, they are again inspected for visible defects injurious to the sheets, and marked so as to be easily identified. If an extra good finish on the sheets is required, a surface free even from minute defects is necessary, and bars intended for such high grade sheets may be pickled before being sent to the hot mills.

SECTION III.

DESCRIPTION OF THE HOT MILLS.

Arrangement of the Hot Mills: A hot mill unit consists essentially of one or two stands of rolls, a pair furnace, one or more sheet furnaces, and a squaring shear. In this country two stands of rolls are generally used, in which case one stand of rolls is known as the roughing or soft mill, and the other as the finishing or hot mill. Under certain conditions, one roughing mill may serve two finishing stands, but preferably each mill consists of the two stands. Both stands are of the two-high non-reversing type, and are arranged in train, usually with one or more other mills, all of which are driven from the same shaft at a speed of from 30 to 38 r. p. m., through spindles and couplings connecting the bottom rolls of the different stands. The number of stands in a train and the manner of driving vary considerably. Old plants have but few mills in train, seldom more than six stands and frequently but three or four, and it appears that a favorite way of driving them was by means of a low-speed direct-connected engine, which required a large and very heavy fly-wheel to prevent the stalling of the engine on the peak loads. As frequent stalling of the engine took place in spite of the large fly-wheel and since the fly-wheel itself was sometimes a cause of serious accident by breaking or bursting, high-speed engines with rope or gear drives were substituted.

Drive for Modern Mills: The gear connection made it advantageous to drive the roll train from the center, thus lessening by half the torque on the spindles and couplings, while still driving as many rolls as with the old end-drive arrangement. In new mills electric motors, geared down from their normal speed of 100 or 350 r. p. m. to about 30 r. p. m., are frequently used, though they have by no means replaced the steam engine. Thus, one of the most recent installations, completed in the early part

of 1921, is steam-driven. This mill, which is driven through a reduction gear from the center, is made up of four hot mills and one stand of cold rolls on one side and three hot mills with four stands of cold rolls on the other, making in all nineteen stands of rolls in the one double train.

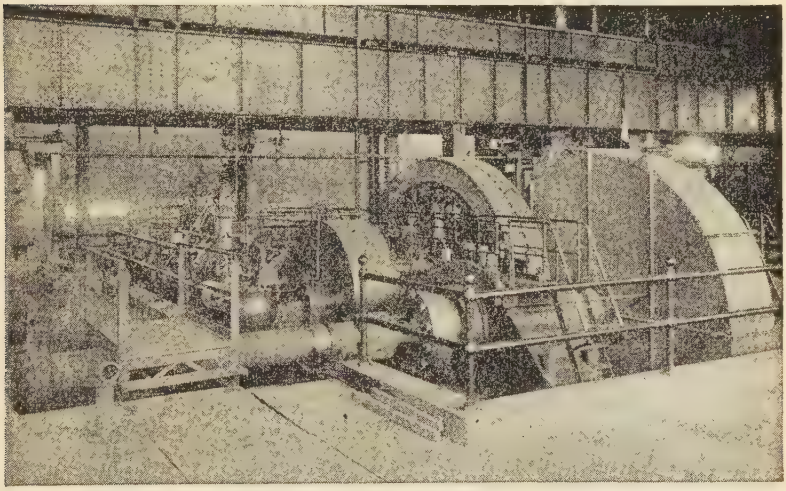


FIG. 250. New Hot Mill Engine.

Arrangement of the Accessories of the Various Mills: With the rolls thus set up in a train, the furnaces are arranged in a line parallel to and in front of the roll train, and the shears, placed in a similar manner, are located on the delivery side of the train. A space about 20 feet wide lies between the furnaces and the roll train, and is known as the doubling floor, or standing, while a space of from 30 to 40 feet in width separates the shears from the roll train, and is known as the cooling and opening floor. Both floors are covered with heavy steel plates, which afford the double advantage of being non-flammable, and of presenting a clean, smooth surface on which the packs of sheets may be shoved about without the danger of scratching them and marring their surfaces. The space comprising the two floors is spanned by overhead electric cranes, which are employed in changing rolls and transporting materials from place to place in the mill building. This building, which may be long enough to house not only the hot rolls but the cold rolls and other accessories as well, extends in width from the front of the furnaces to the farther side of the shears. With this picture of the general arrangement of the mill in mind, a study of the details of the construction of the mills and their accessories may be profitably undertaken.

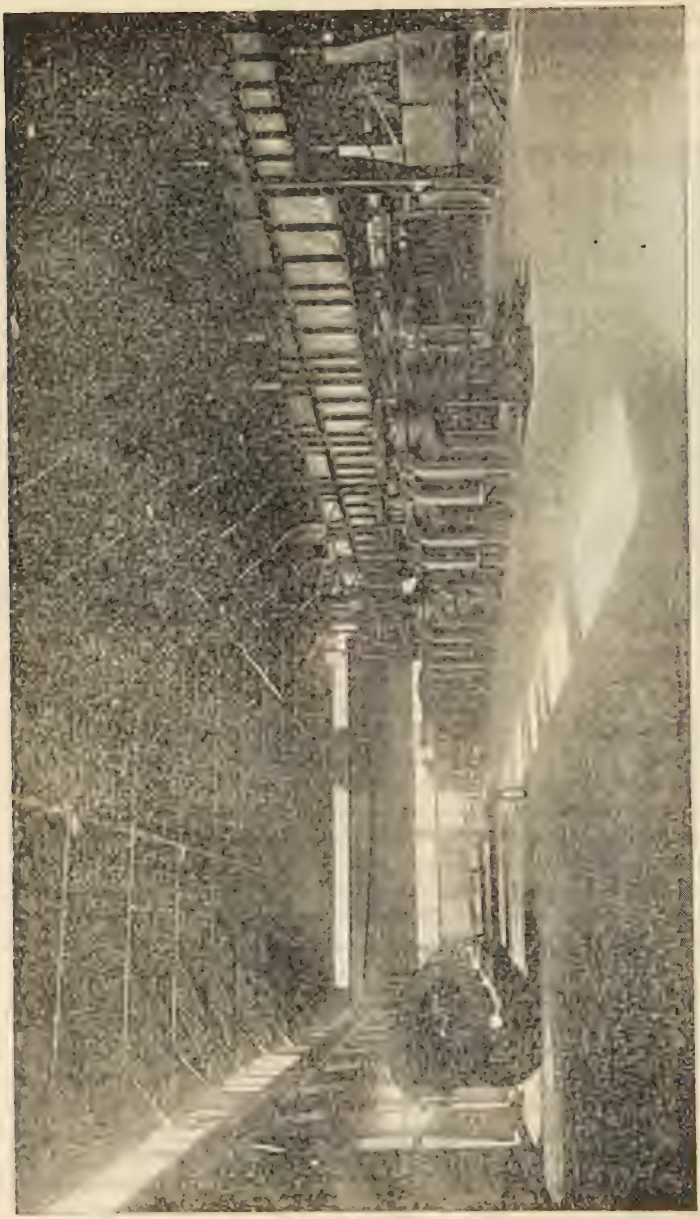


FIG. 251. Arrangement of Hot Mills and Equipment. Showing Furnaces (on the right), a Double Roll Train (center), and Squaring Shears (on the left).

Arrangement of the Furnaces: Each mill is provided with two or more furnaces. One of these is known as the pair furnace and is employed solely for heating the bars preparatory to the beginning of the rolling operations, while the others, of which there are generally two, are known as the sheet furnaces and are used to re-heat the sheets during the hot rolling operations. In some localities, and especially abroad, the first furnace is often called the bar furnace, and the term "pair furnace" is applied to the furnace here designated as the sheet furnace. These furnaces are arranged in various ways. In some mills, designed to roll only light small sheets, as in the case of tin mills, they are all placed side by side, or built enbloc, with doors that face and open directly upon the doubling floor. With an arrangement known as the combination furnace, the waste heat from the pair furnace, which is kept somewhat hotter than the sheet furnace, is used to heat the latter. But this arrangement makes it difficult to keep the temperature of the sheet furnace uniform. Consequently, as a rule, the furnaces are fired independently, and, in mills designed to roll large sheets, the pair furnace is built as a separate unit and is often located at a convenient point just back of the sheet furnaces, which, as a matter of convenience, must always open upon the doubling floor.

General Features of Furnace Construction: As the temperatures required are low as compared with those of other furnaces for manufacturing steel, that of even the pair furnace seldom exceeding 1000° C., the sheet furnaces, and usually the pair furnaces also, are built of ordinary fire brick, are of the reverberatory type, and are devoid of all waste heat appurtenances. In this simplest form, the horizontal section of either furnace is almost square. It consists essentially of a combustion chamber, or fire box, and a heating chamber, separated from each other below by a high bridge wall, over which the flames from the combustion chamber may pass directly into the heating compartment. The combustion chamber varies in size and construction according to the kind of fuel used, which may be either coal, oil, or gas. When gas is used, the combustion chamber is little more than a narrow brick-walled compartment, directly into which the gas is introduced through properly designed burners. When coal is used the combustion chamber is made somewhat larger with grate bars to support the fuel and admit air for combustion. In old furnaces the coal is fed by hand, and the fire box is very simply constructed; but in more modern furnaces mechanical stokers are employed, because these give a more uniform temperature and a flame that varies less in character than that produced by the intermittent firing by hand. As they are usually constructed, the heating compartments of both the pair furnace and the sheet furnaces are very similar. In both cases, the floors are made of deeply corrugated brick, so that the hot gases may come in contact with both surfaces of the bar or sheet as it lies on the floor, and the sheet or bar can be easily grasped with tongs. The exit flues are located in front and near the floor, so that the hot gases from the combustion chamber

will be drawn downward toward the floor of the heating chamber by the draft from the stack, which is located in front and directly over the center line of the furnace. Access to the heating chamber of the sheet furnace is had through two large lifting doors, while several smaller doors are provided in the front of the pair furnace.

The Hot Mill: As previously indicated, the hot mill may consist of but a single stand of rolls, on which all the rolling from bar to finished sheet is performed, or of two stands, one of which is used for roughing down the bar and the other for finishing the hot rolling of the sheet. In order that the reasons for using roughing and finishing mills may be more readily understood, it is necessary to describe the finishing mill first.

Size of Rolls: The rolls used on the finishing mill are always of chilled cast iron, the depth of the chill being ⅞ inch. In size, the rolls vary, roughly, according to the size of sheet the mill is designed to roll, and range from 22 x 30 inches to 32 x 60 inches. Usually, it is considered that the roll should be about six inches longer than the width of the widest sheet the mill is expected to roll, and heretofore the diamater was roughly proportioned to the length, though in general there appears to have been considerable leeway in regard to these proportions. For example, such sizes as 22 x 30, 26 x 30, 22 x 40, 28 x 34, 24 x 48 and 24 x 54 are found in use. In new mills, however, the tendency is to use the heavier rolls on all mills, and 32 inches is fast becoming a standard diameter.

Turning and Dressing the Rolls: The rolls must be very carefully finished, and their surfaces must be kept smooth at all times. This condition is maintained by frequent use of scouring blocks on the rolls as they revolve in their housings and by re-dressing them at regular intervals,—usually semi-weekly. New rolls are received from the roll manufacturer in the rough. They are first carefully centered, and then, with the center holes as bearings, the necks are turned down in a lathe to the correct diameter, which is nearly 4/5 of the diameter of the body. The roll is then placed in another lathe, and, with the necks as bearings, the body is turned down to correct contour. Since no water can be used on the hot finishing rolls, they become hot in service, and, to compensate for the subsequent expansion, the body of the roll must be turned slightly concave. The depth of this concavity varies from 1/32 to about 1/16 inch, a difference in diameter of from 1/16 to 1/8 inch, depending upon the size of the roll, the kind of material to be rolled and whether or not the compensation is made in but one roll or both rolls in a stand. There are different methods of cutting in this concavity, but the method most nearly accurate is that of the crossed roll, or crossed straight edge method. In this method, the body of the roll is turned down until the top roll or a chalked straight edge crossed on the roll a certain amount, depending upon the depth of concavity desired, shows a bearing on the surface of the roll for its entire length. The accompanying illustration shows one method of mounting

the top roll in the turning lathe. This work must be performed with great care as to accuracy, for if the body, or barrel, of the roll is not symmetrical and perfectly in line, or true, with the necks, the sheets will be thinner in some places than in others and will buckle in rolling.

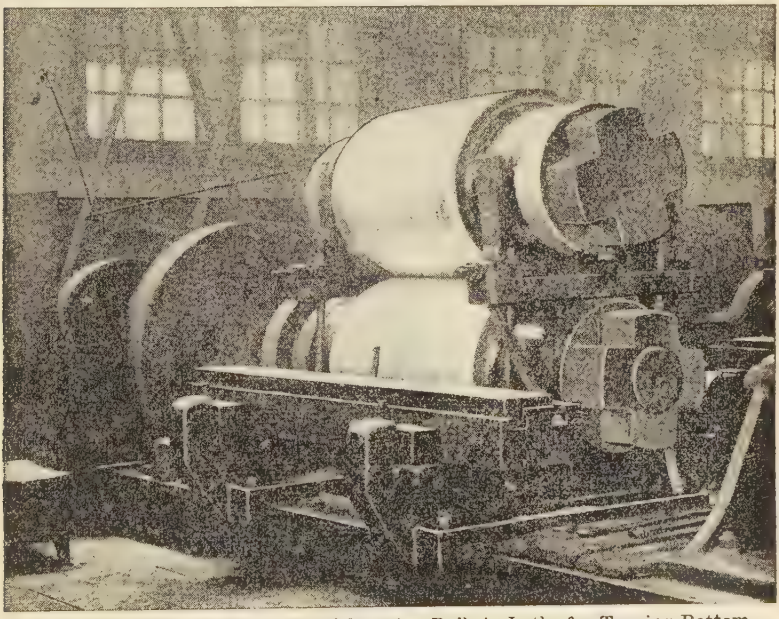


FIG. 252. Showing Method of Mounting Rolls in Lathe for Turning Bottom Roll Concave.

The Housings are of cast steel, very heavy, and of the closed top type, in order to secure the rigidity required for accurate work. When in a working position they rest upon and are fastened to two shoes or plates which are firmly bolted to the two walls of a mill foundation, made of brick laid in cement, or of concrete. Each of these shoes or plates carries a slot that extends longitudinally for its entire length, and by means of this slot the feet of the housing may be bolted firmly to the plates at almost any point along them, eight heavy bolts being used for this purpose. The housings thus support the rolls directly over the mill pit, which is the deep trench-like space enclosed by the two walls of the mill foundation. The windows are but slightly larger than the diameter of the necks of the roll, hence the housings must be spread, that is, one housing moved aside, to remove the rolls from them. When the rolls are in place, they are supported by bearings that fit up snugly against the shoulders of the rolls to hold them in place longitudinally. These bearings for the bottom roll, which is driven, are somewhat heavier and deeper than those of the top

roll, which lies upon the bottom roll and revolves with it by friction. These bearings for the top roll are placed above and upon its necks, so that the chocks act as supports for the breaker blocks upon which the mill screws are seated. To hold the top roll in alignment with the bottom roll, side bearings are bolted one to each side of the window.

The Screws, passing through bronze nuts in the centers of the tops of the two housings, are each capped with a large wheel, known as a spanner wheel. These wheels are of one or two types. In one the upper edges of the rims of these wheels contain a number of large notches or slots. In one of these notches on each wheel is placed a long lever, the short arm of which is anchored to the screw itself as a fulcrum. The long arm of each of these levers is bent downward so as to be easily reached by the roller, and the two levers are tied together by means of a steel bar, known as the spanner bar. This arrangement causes both levers to move together, so that the same pressure is exerted by both screws, and gives the roller complete control of the draft at all times; but since the levers cannot be moved through much more than an arc of 90 degrees, a quarter-turn, and the pitch of the screws is only about one inch at the most, it limits the spread of the rolls to about ¼ inch. A greater spread of the rolls is undesirable on account of the fact that the jump of the top roll on entering thick pieces is very destructive to the mill. In the other method of operating the screws, the upper edges of the rims of the spanner wheels contain teeth like a bevel gear. These mesh with small bevelled pinions mounted on a small shaft that extends from housing to housing. One end of this shaft projects out over one housing and carries a spoked wheel of very large diameter. This wheel can readily be turned by hand, thus adjusting the mill screws and the top roll as desired. Both of these types of screw-down are shown in Fig. 253.

Rigging: Almost opposite, or a little above, the nip of the rolls, are placed the rest bars, which extend from housing to housing on both sides of the mill. On the entering side of the mill, or the roller's side, these bars support a large flat plate, known as the fore plate, the function of which is to support the bar or sheet until the roller can grasp it properly with his tongs and direct it accurately into the mill. On some mills a leg similar to the catcher's leg, to be described shortly, is also provided. On the delivery side, or catcher's side, the rest bars help to support the catcher's rigging. This consists of guides attached to the rest bar to direct the path of the sheet upward as it passes through the rolls; horns also attached to a rest bar, to aid in properly directing the sheet or pack; the billy, which is a small idle roll placed almost opposite the center of the top roll, to make it easier for the catcher to return the sheet over the top roll to the roller; and the leg, a long steel bar extending back some eight or ten feet from the rest bar with one end bent down at right angles to rest on the mill floor, thus forming a support for the long pliable sheets,

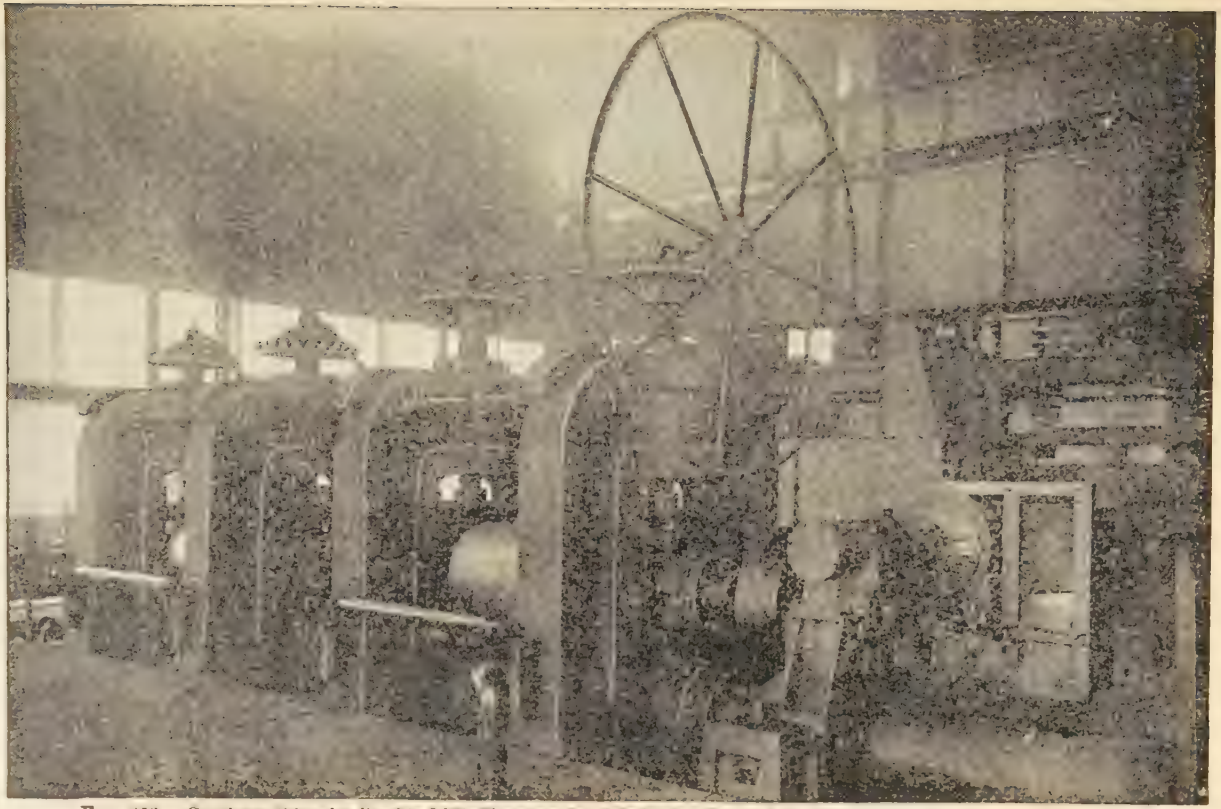


FIG. 253 Catchers Side of a Double Mill, Showing One Method of Driving the Top Roll of the Roughing Stand by means of an Electric Motor Connected through a Worm Drive and Slip Clutch.

which the catcher must direct from one end with his tongs. On mills rolling heavy sheets, two legs fitted with small rollers and with fulcrums near their centers are provided. As the sheet comes through the rolls, it moves out upon the two legs, when the catcher, by bearing down on the end farther from the rolls, elevates the opposite end, so that the pack can be passed over the top roll to the roller with but little effort. With this arrangement, the horns and billy are omitted.

The Spindles and Coupling Boxes: It is to be especially noted that only one roll of a stand used for finishing sheets can be driven, because the driving of both rolls causes the sheets of a pack to weld together. Besides, the driving of but one of the rolls is a great advantage in operating the mill. On account of the greater advantage in construction the drive is always made through the bottom roll, leaving the top roll to be driven by friction. The spindles and coupling boxes for driving the bottom roll are similar to those on other mills, except that the spindles are long, to give the room required between mills, and are always supported in the middle or at each end by bearings.

The Doubler: One more item, the doubler, is necessary before the equipment of the mill is complete. The doubler is placed on the doubling floor to one side of the mill and about half way between the mill and the sheet furnace. It is nothing else than a steam or compressed air hammer with a long narrow flat face, and is used for flattening the curl of a pack after it has been doubled by hand with the tongs.

The Soft Mill: From the preceding description, it is seen that the size of bar that can be rolled by the single stand method is limited in thickness to ¼ inch, or a little more. Hence, long sheets of heavy and medium gages cannot be rolled by this method. To make it possible to roll such sheets, the roughing mill is employed in conjunction with the finishing mill. In this method the bar is roughed down, to a thickness that can be entered into the finishing rolls, on the roughing mill, which is placed in train with and next to the finishing stand. Because the rolls in the mill carry no chill, it is usually spoken of as the soft mill, but sometimes it is designated by the terms roughing mill, break-down rolls, jump mill, or balanced mill. The last two terms refer to the two different kinds of soft mills.

The Jump Mill is practically identical with the hot finishing mill in construction. Usually, the screws are operated by means of a large hand wheel mounted on a shaft with two beveled pinions that mesh with teeth cut in the beveled rim of the spanner wheels. The rolls may be kept cold by means of water sprays like those on plate mills. As the jump roll mill is simple, and, wear and tear neglected, economical to operate, it serves its purpose very well for roughing light bars, but for the heavier

FIG. 254. Roughing Stand. Showing Motor Driven Screw-Down and Method of Driving the Top Roll Through Pinions.

bars it is very expensive to operate on account of the up-setting effect, the danger of gagging, that is, stopping, the top roll by too much draft, and the general disrupting effect of the repeated shock produced each time the piece is passed through the mill. For the heaviest bars the mill is wholly impracticable.

The Balanced Mill: These disadvantages inherent in the jump mill are overcome by balancing or supporting the top roll in such a manner that it is always held up against its chocks and will rise and descend with the screws. This accomplishment involves several changes or modifications in the construction of the mill. Thus, it is not only necessary to provide means for balancing the top roll, but also to change the method of driving it and to alter the scheme for operating the screws, for with the top roll supported out of contact with the bottom roll, it cannot be kept revolving by friction, and to break down the heaviest bars to a size that can be taken by the finishing mill, the balanced roll screws must be turned through one to two complete revolutions. Each of these changes, the balancing of the top roll, the drive for the top roll, and the screw-down, may be effected in several different ways. Thus, the top roll may be balanced either by counter weights or by means of springs placed on top of or under the housings, the latter being considered preferable. It may be driven through pinions and spindles, as in ordinary merchant bar mills; by power transferred by chains or gears from the bottom roll; or by an auxiliary motor drive. On light balanced mills, the screws are actuated by means of a large hand wheel mounted on a shaft with two pinions that mesh with teeth cut in the spanner wheels, as explained in connection with the jump mill. In mills recently constructed, a small electric motor is mounted on top of one of the housings and drives the screws through a system of gears, preferably a worm gear. For indicating the draft on the mill, chalk marks on the spanner wheel are used, or a graduated circle or drum mounted on one of the screw heads is provided.

The Shears used for trimming the sheets to size after rolling are of the guillotine or vertical type, shown in Fig. 255, with blades long enough to permit an edge of all but the longest sheets to be cut at a single stroke. The shear table on which the sheet pack is supported during the shearing is made with two arms, one parallel to the shear blade and the other at right angles to it, in the same relative position as the arms of a carpenter's square. Along the outer edge of each arm is placed a straight edge and a gage to assist the shearman in making parallel cuts and in shearing the pack to correct width and length. A number of clamps, actuated through a cam shaft mounted on the front side of the shear frame, descend upon the pack at the beginning of each shear stroke and hold it firmly upon the shear table while the cut is being made.

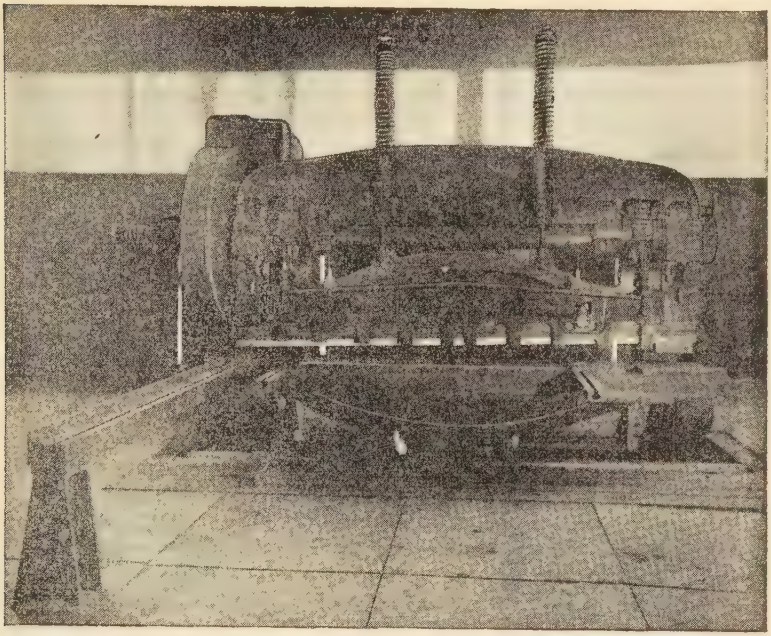


Fig. 255. Front View of 156-inch Squaring Shear.

Hot Levellers: The heaviest sheets are usually levelled, or flattened, hot, like plates, and for the same reasons. Therefore, large heavy mills are usually equipped with a roller levelling machine, which is located so that the sheets can conveniently be passed through the levelling machine immediately after the last pass through the finishing rolls.

SECTION IV.

THE OPERATION OF THE HOT MILLS.

The Mill Crew: The men directly concerned with the operation of the mill during a shift constitute the mill crew. There are three shifts in a day of 24 hours, so each crew works for a period of eight hours each day. The number of men in a crew varies, depending upon the size of the mill and the kind, class or grade of material to be rolled. The chief positions are designated as pair heater, sheet heater, roller, bar roller or rougher, catcher, matcher, doubler, shearman, leader and opener. Added to these, there are a varying number of helpers. The duties connected with these positions are indicated by the titles, with the exception of the roller, who has charge of all the rolling operations and receives the highest pay of any man in the crew. On light mills the shearman, who is assisted

by the leader, may serve two hot mills. The work is so divided as to provide a way for "spelling" the different members of the crew, for no man is required to spend the whole eight hours at continuous labor, but is given regular intervals for rest.

Heating the Bars: After the bars have been sheared to length, as previously described, they are delivered by crane or truck to the pair furnace. Here they are usually charged into the furnace in lots of from 8 to 20 pairs, 16 to 40 bars, which are known as heats. The exact number of bars in a heat depends upon the manner of rolling, which in turn is largely determined by the size of the sheets. Considerable skill is required to heat the bars properly. They must be heated uniformly, and, while it is desirable to have them as hot as practicable for the rolling, care must be taken, especially in the case of pickled bars, to see that they are not heated beyond a certain temperature, else "a scale will be raised" and it will be difficult to secure the smooth surface desired. The maximum temperature for common bars is about 850° C. (1560° F.), while the upper limit for pickled bars is somewhat lower. These temperatures impart a dark cherry red color to the bar in indirect sunlight, and must be determined by the eye, as pyrometers are useless for this work. The uniformity of temperature so much desired is obtained by properly handling the bars in the furnace. As the bars are being charged, the different pairs in a heat are laid, usually, side by side in the back part of the heating chamber next to the bridge wall. Here they are allowed to remain until they have reached a certain temperature, when they are collected and laid in a pile in the front of the furnace and to one side of a door, leaving the rear of the chamber free to receive the next heat, which is immediately charged in the same manner as the previous heat. The bars in the first heat, left piled thus, are allowed to soak until they are required by the mill.

Precautions to be Taken in Heating Pairs: Only a limited time is permitted to accomplish this heating, as the efficient operation of the mill requires that it be supplied with a pair of hot bars at regular intervals of time. Hence the heater must see to it that a fire sufficient to supply abundant heat is kept up at all times. The furnace temperature can then be nicely regulated by means of the stack damper. As an aid in preventing the surface of the bars from being oxidized, the amount of air let into the combustion chamber is a little less than that required for complete combustion of the fuel, so that a long smoky flame, making the atmosphere of the heating chamber almost reducing in character, is maintained. When the bars have soaked in the furnace a sufficient length of time and the mill is ready to begin rolling, the bars are removed in pairs by means of tongs in the hands of a helper and carried to the soft mill. In order to ease the labor of performing this task, heavy mills are provided with an overhead trolley, which, by means of a hooked rod or a chain, may be employed to support the tongs and the load in transit.

Breaking Down the Bars: The helper deposits the two bars upon the fore plate of the roughing mill, where any loose scale or dirt is removed by a few strokes with a steel brush. With the mill screws adjusted to effect the proper draft, the rougher then immediately grasps one of the bars with his tongs and passes it through the mill, to be grasped with tongs by the catcher on the opposite side of the mill. Then while the catcher is elevating the bar, using the billy for leverage to return it over the top roll, the rougher feeds the second bar into the mill and grasps the first, which the catcher is now steadying on the top roll for the second pass. As the screws are quickly adjusted, this pass is made at once. These movements are repeated in rapid succession until the bars have been roughed down to the gauge that can be taken by the finishing mill. From this point, the manner of completing the roughing is adapted to the gage of the sheets. On the finishing mill, the pairs are handled in the same way as they were on the roughing mill for a number of passes until the single pieces are about $\frac{3}{32}$ inch thick. The two roughed down bars are then matched, that is, placed one upon the other, and rolled for the last two or three roughing passes. After roughing down, these sheets must be parted, a result that is accomplished by grasping one corner of the top sheet with tongs and pulling upward while the bottom sheet is held down with the foot. As a rule, the roughing down is continued until the bars have been elongated to one-half the length of the sheet desired, or to a gage that gives a weight per square foot twice or four times that of the finished sheets. Sheets heavier than 16 gage are generally finished at once without reheating, but all sheets of lighter gage must be reheated to complete the rolling.

Special Operations for High Grade Sheets: The method of procedure after the break-down, or roughing, depends upon the grade, the surface finish, and the gage of the sheet. On high grade sheets requiring a surface perfectly smooth and free from all defects, such as automobile sheets, it is the practice in some plants to pickle after the break-down. This method is more expensive than pickling the initial bar, but has the advantage of removing or revealing any defects that may have been developed in the heating and rolling operations of roughing. For this process, a pickling machine of the plunger type, which will be described later in connection with finishing processes, is employed, and the heavy rough sheets are pickled and washed in the usual way. These sheets are then carefully inspected, and those that show evidence of injurious defects are discarded.

Methods of Hot Rolling: The succeeding operations are varied and modified somewhat to adapt them to the gage of the sheet. Generally, sheets of 13 gage or heavier are rolled singly, or one at a time, while sheets lighter than 13 gage are finished in packs of two or more sheets. The number of sheets in a finished pack varies from two to eight, according

to the gage. Thus, sheets of 14 to 18 gage are finished two in a pack; 19 to 22 gage, three in a pack; 23 and 24 gage, in some mills 20 to 27 gage, four in a pack; 25 to 28 gage, in some mills 27 to 29 gage, six in a pack; 29 to 34 gage, in some mills all sheets lighter than 25 gage, eight in a pack. For ordinary grades, the packs of four and six sheets each are made by doubling single packs of two and three sheets, respectively, hence are known as doubles, or double iron. Packs of eight sheets are sometimes built up by doubling single packs of two sheets each twice, hence are called double-doubles, or double-double iron. On account of the danger of forming bucklers if the curl on one end is not sheared off, double-double packs are undesirable, and if bars sufficiently light are available, packs of eight are made up by matching and subsequently doubling four break-downs. Sheets that are finished singly, or in packs of two or more without doubling, are designated as singles, or single iron. For extremely light gages, 34 to 36, two packs of eight are sometimes tagged, that is, matched for the last finishing passes to make a pack of 16 sheets.

Final Hot Rolling Operations: The operations necessary to prepare the break-downs and build up the packs for the final rolling operation are commonly referred to as opening, matching, doubling, reheating, and running over. From the preceding paragraph it will be surmised that these operations are subject to much variation, both as to number and sequence, according to the gage and size of sheet to be rolled. Not all these operations are necessary in rolling single iron, but all are for double iron and some must be repeated one or more times. Furthermore, the manner of performing each separate operation varies according to the practice of the mill, which in turn is determined largely by the grade of sheets to be made, the equipment at hand, the ideas of individual operators as to best means of attaining the aims sought, and other local conditions. Therefore, it is practically impossible to describe these operations accurately without giving details that may result only in confusing the matter in the mind of the reader. However, definitions of the terms will suffice to give an idea of the great amount of work necessary to produce some sheets. After each rolling operation the pack must be opened, that is, the sheets, which have a tendency to stick together, must be separated from each other. This is done by a workman, who, after loosening a corner of the pack by bending or otherwise, grasps each sheet with tongs and pulls it loose from the pack. Matching refers to the manner of placing the parted sheets together to form a new pack that can be rolled so that all the sheets in the pack will be of proper gage. Doubling is an operation necessary only in rolling double or double-double iron. It consists in folding the parted and matched sheets end to end to give a new pack of double the number of sheets. Reheating, of course, refers to the heating necessary before each rolling operation. This heating must be done with great care, so that all parts of the pack will be heated uniformly to the same temperature, which must be as high as possible without raising scale on the surface or unduly in-

creasing the tendency of the sheets to stick together in the pack. Running-over refers to any rolling operations on the finishing mill that may be necessary to reduce the thickness of the sheets in a pack to a point where they may be brought to the gage or thickness desired by one rolling operation. In the final rolling operation, the reheated pack is passed through the mill a number of times, the screws being adjusted previous to each pass, until the sheets have been elongated to the length desired, plus a suitable allowance for scrap. Unlike heavy plates, sheets cannot be gaged during the rolling, since they must be rolled in packs. Rolling to length, therefore, is the only means of controlling the gage during this operation. After the final pass, the catcher draws the pack back out of his way upon the cooling floor where it is permitted to lie until cool enough to shear.

Warming Up the Rolls: One of the most important precautions to be observed in the operation of the hot mill is that of properly warming up the rolls. The temperature of the rolls after they have been warmed up and the mill is working steadily is about 350° C. (662° F.)—600° F. to 750° F. is considered a safe working range—and this temperature must be determined by color. The color preferred by some operators is a brownish purple one, though, if the mill is working rapidly, it is difficult to prevent the temperature from rising to the maximum given above, which imparts a dark blue color. The rolls must be heated up to their full temperature very gradually. Therefore, a full turn is usually devoted to this object, for, if the mill were started rolling full-sized sheets while the rolls were cold, not only would the sheets be imperfect—too heavy in the middle with buckles along the edges—but there would be great danger of breaking the rolls. Even if the rolls did not break at the time, they would surely be cracked internally, and would break at some not distant future time.

Internal Stresses of Chilled Rolls: A word of explanation will serve both to show the reason for this fragility of the rolls and to emphasize the importance of care in this matter. To begin with, the rolls are under tremendous internal stress from casting. Having been cast in chill moulds, the hard outside cylindrical portion known as the chill is solidified while the central portion is still molten. When this central portion finally cools down, the resultant contraction has the effect of putting the outer shell under a permanent compression and the inner shell similarly under tension. Now, if the rolls be warmed up to rolling temperature rapidly, the outer shell is forced to a higher temperature than the central portion, and the resultant unequal expansion causes an increase of both the stresses already acting on the roll. Then, since the compression strength of cast iron is much higher than its tensile strength, also, since its ductility is very low and its coefficient of expansion is high, a comparatively few degrees difference between the outer and inner portions may suffice to stress the latter beyond its elastic limit, when an internal crack is the inevitable

result. As iron is a good conductor of heat, this difference in temperature between outer and inner portions and its evil consequence are easily avoided by warming them slowly enough to give the heat time to travel into the roll, thus causing all parts of the roll to expand at about the same rate.

Plan for Warming Rolls: There are several different ways by which the rolls may be warmed up properly, but the old method of using hot bars and narrow sheets for the first, or warming up turn, is still generally employed. By this method, the usual plan is to start the warming up turn by rolling a number of light short bars. These bars, which are scrap ends collected for the purpose, are heated to a moderate temperature and then roughed down slowly, the roller being careful to feed them into the mill so as to warm up the rolls uniformly about their circumferences. After reheating, these bars may be rolled into sheet form and discarded. Then, when the rolls have begun to show a straw color, the rolling of sheets for the trade is slowly and cautiously begun.

Order of Rolling: As the mill is very hollow at this time, only the narrowest sheets on the schedule are rolled during the warming up turn. Thereafter, the width of sheets to be rolled is gradually increased, until the mill is rolling the widest sheets scheduled for the rolling. Then, as the rolls wear away in the middle, and the mill begins to get hollow again, the widths of the sheets rolled are gradually decreased. In this way the gage of the sheet is kept most uniform, and such defects as buckles and pinches are avoided. The roller judges the hollowness of the mill from the appearance of the rear end of the pack as it is being rolled; a hollow mill elongates the sides of the pack faster than the central position, producing a fish-tail effect, or projections known as horns on this end of the pack. Recently electrically heated jackets for the rolls have been devised, which provide for the gradual warming up of the rolls before rolling is begun. Gas heaters are also being successfully employed for this purpose. With these devices the mill may start the first turn rolling full width sheets, but as the economies to be effected depend upon local conditions, it is difficult to predict to what extent they will be adopted.

Other Precautions to be Observed in Rolling Sheets pertain to the general care with which the mill is operated. The necks of the rolls require constant attention to see that they are properly lubricated and do not become too hot. As iron is a good conductor of heat, a small jet or spray of water directed against each neck is required to absorb the heat conducted there from the body of the roll. For lubricating the necks, a special hard petroleum grease is employed. This grease is melted usually by steam coil in grease boxes attached to the housings, and is applied to the necks with a swab as required. Care in applying this grease must be exercised to see that none of it splashes upon the body of the roll, for it chars on the hot roll, pits the sheet, and generally marks the surface

of the roll. Care is also required in regulating the draft in rolling, for too much pressure applied to the rolls, aside from the danger of breaking them, may cause the sheets to stick in the pack, even though they were heated properly, and may also cause **gathering,** a peculiar condition in which small spots, or patches, of the surface of the top sheet in a pack sticks to the roll, apparently as if welded there. These patches welded to the rolls cause pits in the sheet, and as soon as gathering occurs the rolls must be scoured clean again. This scouring is accomplished by means of an emery or carborundum stone cut to the contour of the roll or of the nip of the two rolls and attached to one end of a long rod or pole. Using this pole as a lever, and a rest bar, or a cross bar extending through holes in the housings especially provided for the purpose, as a fulcrum, this stone is forced against the revolving rolls so as to grind out the defects very smoothly. There is a constant tendency for the rolls to become rough, so that they need to be scoured at regular intervals whether the gathering is noticeable or not. When the rolls have become so badly worn that it is difficult to get the finish required on first grade sheets, they are taken out of the mill and redressed in a lathe, a new or a redressed set being put into the mill in their place.

Shearing the Sheets: The pack, after the last pass through the hot mill, resembles a single heavy sheet with rough and irregular edges. Therefore, as soon as it has cooled to, or nearly to, atmospheric temperature, it is sheared along all edges to remove the excess metal, true up the edges, and square up the sheets to the length and width desired. To accomplish these ends, the shearman and his helper lift the pack by hand to the shear table, shear off enough of the excess metal along one side to straighten the edge, and then, transferring the pack to the shear side- or end-table, he presses the sheared side-edge of the pack against the straight edge there provided and similarly shears off one end. These processes are then repeated in shearing off the remaining side and end, except that in these cases the edges already sheared are held firmly against the gage stops on the table, so that the cuts will be made to give the proper width and length. With all edges properly sheared, the pack is put aside upon the opening floor.

Opening the Pack. The separating of the sheets in the packs requires considerable labor. The opening is usually begun by bending one corner of the pack back and forth with a pair of tongs. This bending tends to cause the sheets to slip upon each other, and generally results in loosening the corners of the sheets so that they can be parted enough to be grasped one at a time with tongs. Then, by giving a sudden pull, the top sheet may be loosened for its full length. If any of the sheets are sticking together, they are put aside to be opened at a convenient time by swording. This act consists in parting the sheets to the area that is sticking, and holding them apart while striking into the nip of the two sticking surfaces

with a long, broad-bladed, knife-like tool made from a piece of heavy sheet iron. If this treatment tears the sheets or fails to part them cleanly, they must be discarded. As the pack is being opened, the opener also assorts the sheets, discarding all those that contain noticeable defects that will be harmful to the finished sheet.

Variations in Hot-Rolled Sheets: Sheets completed up to this stage are known as hot-rolled-only. From the preceding descriptions it should be plainly evident that gage or weight variations in these sheets are unavoidable. To begin with, the sheet bar itself carries certain weight variations, which, due to variations in rolling temperature, wear on the rolls and their bearings, and limitations as to accuracy in mill adjustment, cannot be avoided, but is kept to a minimum with constant attention to roll adjustment of the bar mill. Second, due to the fact that the sheet bar can be made only in weights ranging in tenths of a pound for the lighter bars and quarters of a pound for the heavier bars, it is not always possible to apply bars of exactly the theoretical weight required by the sheet. Then, if the sheets are of high grade, the pickling of the bar or break-down introduces another loss that is somewhat variable, though every attempt be made to keep it constant. Next, the rolling introduces a third or fourth gage variable, because, if the sheets are rolled in packs, those in the middle of the pack are elongated more than those on the outside, which are cooled more rapidly on account of coming in contact with the air and the colder rolls. In making his final gage test, the roller must roll the pack down until the shortest sheet in the pack measures up to the length required, but an extra pass to roll the shortest sheet in the pack out to this length invariably results in elongating some of the others too much. Furthermore, though the screws be set with accuracy, there is a difference in draught on the front and rear ends of the pack, due to the inertia and the spring of the mill, and also in different parts of the pack, if the temperature of the pack is not uniform for rolling, or if the rolls become slightly puffed from overheating or hollow from wear or too little heat. Finally, there is a variation, due directly to all these other variables, in the scrap loss on shearing. Throughout the process there is the human element contributing to these unavoidable mechanical variations, which may be increased many times by careless work. In the face of all these variables, the usual weight tolerance of $2\frac{1}{2}$ per cent. over or under, which in the case of very light sheets may mean less than one thousandth of an inch in thickness, appears small rather than generous; yet sheets are being produced well within this tolerance. In shearing, too, certain tolerances on hot rolled sheets are necessary, though with careful work the variations here can be kept within a narrow range. Few hot-rolled-only sheets are put in service as such, because they lack surface finish, are distorted from the rolling, cooling and opening operations, and are frequently lacking in one or more of the mechanical properties required.

SECTION V.

FINISHING THE HOT-ROLLED-ONLY SHEETS

The Finishing Operations: To the sheet manufacturer, hot-rolled-only sheets, which must be produced about as has been described, represent only semi-finished product. The various uses to which sheets are put require them to differ widely as to size, form, accuracy of dimensions, mechanical properties, and surface condition. Thus, one sheet must have an open, porous surface, and another must have a hard, smooth, highly polished surface; one sheet must be stiff and strong, and another must be soft and ductile. To get this variety in sheets, the processes of manufacture must be varied, and it is a natural result of the uniform conditions under which the hot working must be performed that most sheets after hot-rolling are unfit for the uses to which they are intended. It is the function of the finishing department to remove or overcome the imperfections of hot working and adapt the sheet to the purpose for which it is intended. The processes at the option of the manufacturer for obtaining these results are known as cold rolling, annealing, pickling, levelling, bluing, polishing, and forming, and these operations must be modified in character and varied in number and sequence to give the different finishes, degrees of accuracy, and tensile properties required by the different varieties of sheets, according to the kind of service they are intended for. Thus, we have furniture stock, locker stock, range steel, enameling stock, Japanning stock, stove pipe stock, elbow stock, automobile body stock, automobile fender and hood stock, deep drawing stock, and so on, each requiring a treatment or a series of treatments a little different from any of the others, the description of which would form as many separate stories. As an attempt to trace each product through the finishing processes would necessarily involve much detail description and lead to much repetition, we shall, for the sake of brevity, confine this discussion to a general description of the finishing processes mentioned above and the effects produced, or the results to be obtained, by the application of each.

The Objects of Cold Rolling may be to efface the bends, curves, and kinks in the sheet produced by the cooling and handling after hot rolling, to smooth and polish the surfaces, or to adjust the strength and stiffness of the sheets. Of course, in each pass through the cold rolls there is a slight reduction in thickness with a corresponding increase in length, but in all cases the gage is effected so little that control of the gage of the sheet cannot be considered as one of the principal objects in cold rolling. Its place in the sequence of the finishing operations depends on the result sought. If the first object only is sought, as in the case of sheets to be galvanized, it constitutes the initial finishing operation; if the third object, it must be a final operation; but if the second object or both the second and third objects are sought, the cold rolling may form, along with pickling, annealing, and other processes, two or more steps in the finishing of the sheets.

Construction of the Cold Rolls: In general the cold rolls are similar in size, construction and arrangement to the hot mill. The housings, however, instead of having but one top screw in each, as in the hot mill, are each provided with two screws, placed on opposite sides of the center line parallel with the rolls. After passing through the top of the housing these two screws bear upon each end of the top roll bearing, thus making it possible to compensate the slight crossing of the rolls that can't be overcome with side bearings alone. The bodies of the rolls, each of which presents a very hard chilled surface, are chamfered back from the shoulder for a distance of two or three inches, to prevent the spalling of the rolls that would otherwise occur when the rolls are screwed down tight upon each other. This bevelled portion is usually designated as the grease chamfer. The mill is provided on each side by fore plates and stationary tables for supporting the sheets as they enter and leave the mill.

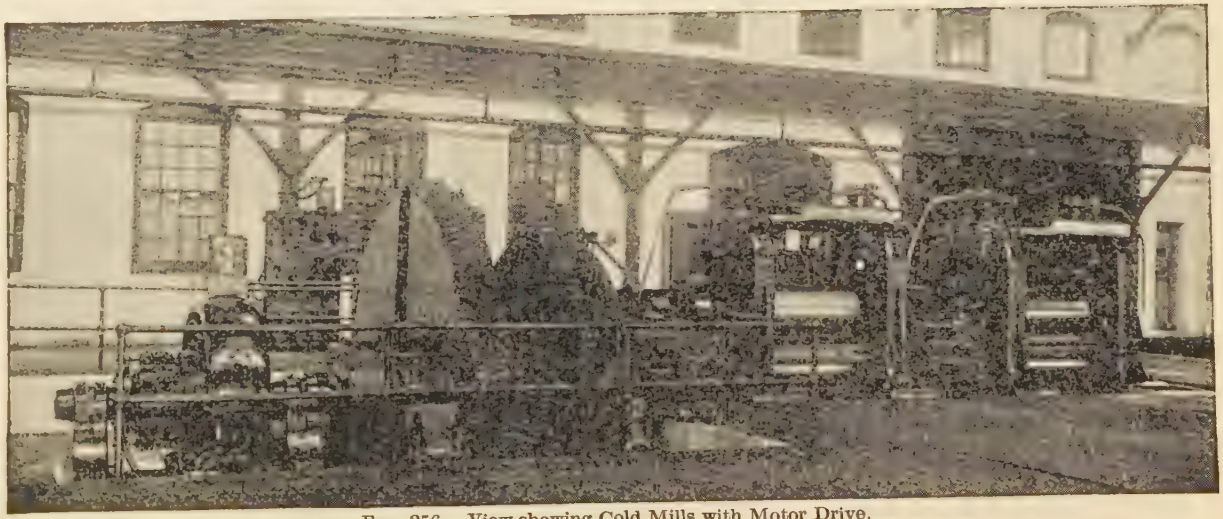


Fig. 256. View showing Cold Mills with Motor Drive.

Arrangement and Drive for Cold Mills: If the plant is a small one and its product is chiefly one pass stock, such as is used for galvanizing, or other material that does not require a specially smooth or polished surface, the cold mills are often driven in train with the hot mills. Working on one-pass stock alone, one stand of cold rolls, working 9 hours a day, can readily handle the product from two hot mills, but, in order to provide for additional cold rolling, most installations provide about three or five stands of cold rolls to four or seven hot mills, respectively. If the plant is a large one, or if its product is mainly highly finished material requiring several passes through the cold rolls with pickling and annealing operations intervening, the cold rolls are generally set apart from the hot mills and at some point convenient to the pickling tanks and annealing furnaces. Here they are set up and driven in train by engine or motor very much as the hot mills are. In rare cases two short trains are arranged in tandem, so that by means of belt conveyors between two opposite stands of rolls, sheets may be given two passes with one handling.

Operation of the Cold Rolls: To an observer not experienced in the work, the operation of the cold rolls apparently consists of the simple act of feeding the sheets singly into the rolls, and receiving them by hand as they leave the rolls on the other side. Their operation, however, requires the constant attention of an experienced and skillful foreman, and, for the best work, the greatest of care on the part of every workman. The rolls must be kept in perfect adjustment, their necks properly lubricated, and their rolling surfaces perfectly smooth. Any lack in the adjustment of the rolls results in a distortion of the sheet and defeats one of the chief objects of the cold rolling. Failure to keep the necks properly lubricated not only causes rapid wear of the bearings, but causes the neck to heat up unduly. This heat is conducted back into the body of the rolls and causes them to become puffed at the ends and hollow in the middle. Even with close attention to lubrication, the rolls will puff a little at the ends, if the mill is working steadily, and to overcome this expansion a gas torch is frequently kept burning under the middle portion of the bottom roll. The high polish on the rolls is maintained by dressing them down with polishing blocks at frequent intervals and running them idly, after and between dressings, for about eight hours each day under sprays of water with the screws down tight. This latter treatment also prevents the rolls from becoming out of round.

Importance of Care in Cold Rolling: In feeding the sheets into the mill, the operator must be careful to see that none of the corners of the sheet are bent back and that no dirt that may accidently fall upon the sheet is allowed to pass through the rolls, as these things may not only spoil the sheet but ruin the rolls as well. To illustrate the harm that may be done by loose dirt on the sheet, one plant found it necessary to reject each day several sheets belonging on an order of automobile

sheets on account of small slightly roughened spots that occurred very irregularly on the surface. In the succeeding investigation to locate the cause of these defects, it was found that they were caused by cigarette ashes which the workman had thoughtlessly allowed to drop upon the sheets as they passed through the rolls.

The Effects of Cold Rolling: As already implied under the objects of cold rolling, this operation, aside from flattening and smoothing out the sheet, produces marked effects upon the surface condition and the mechanical properties of the sheets. By removing the scale and then cold rolling the sheet, its surface may be made very dense and smooth. Again, by bluing the sheet, a process that will be described later, and cold rolling at certain temperatures, a highly polished condition is imparted to its surface, which will resist atmospheric corrosion so long as the sheet is not exposed directly to weathering processes. Each pass through the cold rolls increases the hardness and tensile strength a certain amount and, of course, decreases the softness and ductility in proportion. This fact provides a means of nicely regulating these properties. By annealing, the maximum softness of which the sheet is capable may be imparted, when by cold rolling the hardness and stiffness may be developed to any degree desired within the limits of which the steel is capable. Therefore, when strength and stiffness are required of a sheet, cold rolling may be made the final operation, aside from leveling, which will be described later. In the fabrication of such sheets, it must be borne in mind that the strength and stiffness imparted by cold rolling disappears on heating, and that the sheet may be ruined, or its efficiency much impaired for the purpose it is intended, by such operations as welding or brazing.

Pickling: The pickling process has for its object the removal of scale from the surface of the sheets. It is applied to all sheets that are to be coated with tin, lead, zinc, or enamel, and to uncoated sheets intended for purposes that require a perfectly smooth and highly polished surface. As generally carried on, the operation consists essentially in immersing the sheets in a dilute solution of sulphuric acid, until the scale has been loosened from the surface, and then in fresh water or an alkaline solution, until the adhering acid solution has been removed or neutralized. Hydrochloric acid can be used for this purpose, but on account of its greater cost and several other disadvantages its use is restricted to the one or two cases in which it is absolutely necessary. Two types of apparatus have been devised for carrying out the pickling operation. One of these, which we may designate as the plunger or dipping type, rapidly raises and lowers the sheets in the acid, while the other, which may be referred to as the surging type and is known as a displacement agitator, raises and lowers the acid level during the time the sheets remain submerged in it.

Another type, which we may call the oscillating type, as it moves the sheets back and forth in a horizontal direction through the acid, has been used abroad, but only the first two types have found favor in this country.

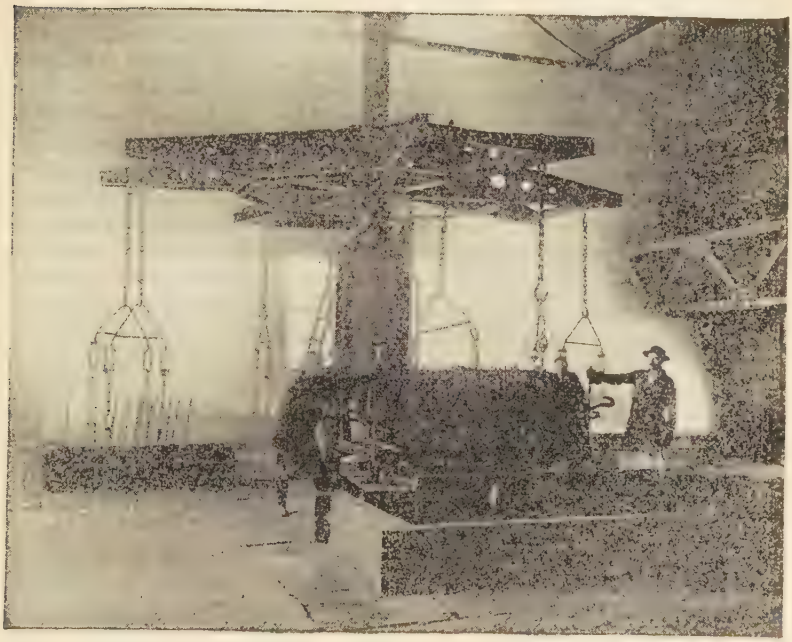


FIG. 257. View of Mesta Pickling Machine in Operation.

The Plunger Principle is well illustrated by the Gray and the Mesta pickling machines. In the Mesta machine a long, heavy piston rod is supported in a vertical position so that the lower end may be connected to pistons of two large vertical steam cylinders, the lower of which is located beneath the floor of the pickling house. The upper end of this rod, rising to a height of 12 or 15 feet above the floor level, supports three or four horizontal arms, which extend outward to points directly over the center line of the pickling vats, or tanks, built in the floor below. These tanks are rectangular in shape, and are built about the plunger so that their longest axes are tangent to a circle described with the cylinder as a center. They are usually about five feet in width and of such a length

and depth that they will contain, on edge, the largest sheets produced by the plant and give a clearance of about 6 inches at each end and 3 feet or more above. Heretofore, these tanks have been constructed wholly of wood, but recently glazed brick laid in molten sulphur has been used to support the wood lining. They are either two or three in number, according to the practice pursued. Two are essential, one to contain the pickling solution and the other to contain the fresh wash water, but a third containing a weaker solution of acid is sometimes placed between these two. When in use, they are filled to within about a foot of the top with their respective liquids. The strength of acid used in the first pickling tank varies from 5 to 7 per cent. and that in the second, where a second tank is used, from 1½ to 2½ per cent. Both are heated with steam to a temperature of from 140 to 180° F. For supporting the sheets, which must be held up on edge, during the pickling operations, crates or cradles made of a special bronze are provided. These cradles are suspended with chains of the same material from the projecting arms of the plunger, and are capable of carrying more than 100 sheets at once.

For Operating the Apparatus the plunger is provided with both a hand and a sliding automatic valve control similar to that used on steam hammers. The automatic control is so adjusted that the plunger has a short stroke of but 12 to 20 inches, but with the hand control, which is used to lift the cradles containing the sheets in and out of the bath, the stroke may be increased to six feet or more. With this contrivance, the crate, which rests on a bench of suitable height and has been loaded with sheets laid edgewise upon it, is lifted by the plunger, swung round directly over the acid bath, and lowered into the acid. As soon as the piston drops to the lower end of the cylinder, the automatic control comes into action, plunging the crate of sheets up and down in the acid until raised by the hand control again. During this process, a second crate has been loaded with sheets, so that when the first crate is raised out of the acid the plunger is swung around again, bringing the first crate of sheets, now fully pickled and free of scale, over the water tank, and the second crate of sheets over the acid bath, when they are both lowered and plunged as before. By constantly adding acid to the pickling bath or baths and maintaining a circulation of the water in the washing tank, the process is, thus, made an almost continuous one. The Gray or mono-rail machine, while differing radically from the Mesta in construction and operation, employs the same principle in pickling, and need not be described here.

The Surging Type of pickling apparatus is commonly spoken of as the Vandergrift pickler and is employed mainly in galvanizing shops. It involves the agitation of the acid about the sheets, which rest on their edges in a position approximately vertical. The construction of this apparatus calls for a strongly built wooden tank about fifteen feet in length,

five to six feet in width, and six to seven feet in depth, inside dimensions. They are usually built into the floor of the shop so that their upper edges rise to a height of about two feet above the floor level. A longitudinal partition divides the upper portion of this tank into two unequal parts, one of which is between three and four feet in width, and the other, twelve to sixteen inches. As this partition extends only to within about six inches of the bottom of the tank, these two compartments are intercommunicating from below, so that acid solution poured into one rises to the same level in the other. The larger of these two compartments is used to contain and support the sheets during the pickling operation, while the smaller contains the agitating device in the form of a wooden float, which has a length and width but a few inches, and a depth of about a foot, less than the same dimensions of the compartment itself. Suitable metal extensions firmly attached to the top of the float at each end connect with a gear driven crank mounted on the outside of the tank, so that, with the proper guides, the float may be raised and lowered through a stroke of about 18 inches. From this description, it will be seen that, with the tank filled with acid to the proper level, the operation of this device brings about a varying displacement of acid by the float in the smaller compartment with a corresponding rise and fall of the acid level in the larger, or pickling, compartment. To wash the sheets, they are immersed for 15 to 20 minutes in fresh water contained in a second tank.

Other Aids to Pickling: Both the concentration and the temperature of the bath are important factors in pickling and should be kept as nearly constant as practicable, because the activity of the solution depends upon them. In starting a vat, the tank is filled to the desired level with water, and concentrated acid is added until gravity, or preferably chemical, tests show that the solution is of proper concentration. A 5-per cent. solution is the strength most often used for all work except in galvanizing, when a 7-per cent. solution is employed. These percentages correspond approximately to 5° and 7° Baumé, respectively. Thereafter, more acid is added as required to maintain this concentration, which must be regulated by free acid determinations on the solution, or estimated through long experience. The temperature of the bath is maintained at 140° to 190° F. by means of live steam, which is injected into the bath through a lead or bronze pipe that extends to and opens on the floor of the tank. With both these factors kept constant, the pickling loss, which, in good practice, should not much exceed 2 per cent., depends upon the time the sheets remain in the bath and the composition of the steel. Copper bearing steel, for example, does not etch as rapidly as plain steels. Many operators use a product obtained in the milling of wheat and known as shorts or middlings, or some other organic addition, as an inhibitor to reduce the pickling loss. This material, by forming a thick scum on the top of the bath, also prevents the escape of the obnoxious fumes evolved in pickling and makes the pickling house a pleasanter place in which to work.

Disposal of Spent Acid: The acid bath may be used until its gravity reaches 1.34, or about 34° to 36° Baumé, when, owing to the concentration of ferrous sulphate, it is no longer efficient as a pickling agent and must be discarded. Therefore, when the gravity reaches about 24° Baumé the operator begins "killing" the bath, that is, he adds no more acid but continues to use the solution for pickling, increasing the time of the operation, until the acid is so nearly spent that it acts very slowly. The bath, containing about ½ per cent. of free acid, is then discarded, used to strip defective galvanized sheets, or converted into sulphate of iron.

Effects of Pickling: Some of the hydrogen liberated from the acid in pickling is, to a greater or less extent, absorbed and occluded by the metal. The occluded hydrogen may cause some trouble in succeeding operations and actually develop defects in the steel. One of the defects accredited to pickling is that of raising blisters in the steel. It is not the sole cause of the blisters, for it is held to be impossible to blister perfectly sound steel in pickling. The great amount of reduction from the ingot to the thin sheet must certainly result in spreading even the small slag inclusions, or sonims, found sometimes in the best steel, into areas many times larger than they originally occupied, each forming a kind of closed pocket. As long as the walls of these pockets remain flat and in close contact the blisters cannot be detected, and are harmless in most sheets, but the occluded hydrogen collecting in these pockets may, under certain conditions, exert enough pressure to separate these walls and raise the blisters, when the sheet is ruined. The occluded hydrogen can be driven out of the sheet by heat, or the same effect is obtained by allowing it to lie immersed in water for several hours.

Annealing Operations: Just as the pickling and cold rolling processes are employed to impart surface finish to the sheet, so annealing and cold rolling afford the means by which the mechanical properties of the sheet may to a certain extent be adjusted. Of course, the chief result sought in annealing is softening or the development of the ductility, which implies the release of rolling stresses and, in most cases, of the rolling strains as well. This softening permits more cold rolling to be done, so in this indirect way, annealing may also contribute something towards the surface finish of the sheet. All agencies and processes, however, have their limitations, and, it is with the idea of leading the reader to a full realization of all the limitations of the finishing processes for sheets that the following description of annealing practice for sheets is written. There are two general methods employed for the annealing of sheets, and these are designated as open annealing and close, or box, annealing.

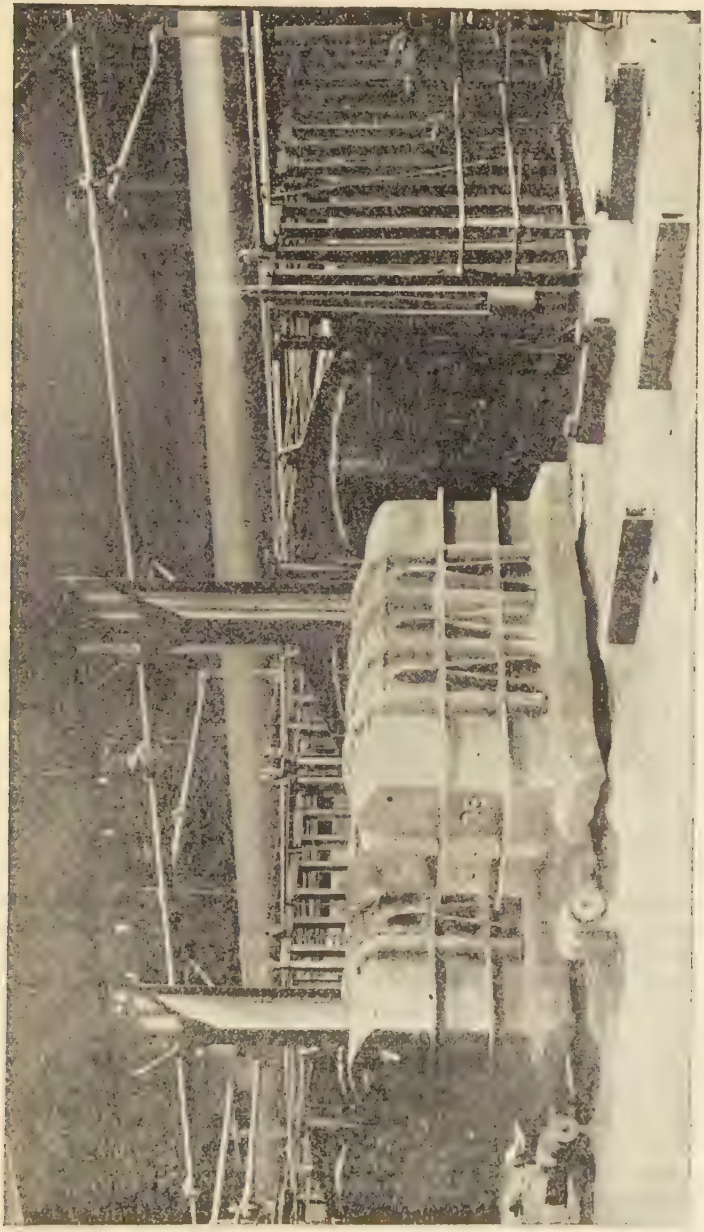
Open Annealing is seldom applied to sheets lighter than 18 gage. As the term implies, it is a process in which the sheet is heated and cooled for annealing without protection from the air. The approved modern method of carrying out this process involves the continuous principle in

heating, and requires a furnace specially constructed for the purpose. This furnace, which is built of the cheaper grade of fire brick, is 40 to 60 feet long and about six feet wide inside. The bottom, which forms the most interesting part of this furnace, is flat and level and stands about 3 feet above the floor of the shop. It is enclosed on the two sides by solid brick walls, and is covered with a low arched roof. Except for shields at the top, the ends of the furnace are open. The bottom is traversed lengthwise by a number of endless chains, to which are attached at frequent intervals a number of steel legs or prongs, all of equal length, for supporting the sheet at a height of about 12 inches above the brick floor. The heat is supplied by a number of gas jets located in the bottom and distributed so as to give a transverse zone of even maximum temperature near the middle of the furnace. With this apparatus in operation the sheets are fed, one after the other, into one end of the furnace and are carried through to the other end, being gradually heated up to the annealing temperature of approximately 1600° F. After annealing, the sheets must be levelled to correct the warping brought about by the annealing. In some plants the sheets pass directly from the furnace to a roller levelling machine.

Effects of Open Annealing: To appreciate fully the functions of open annealing it is necessary to understand the peculiar structural condition of the sheet which results from the hot rolling. Since the bar previous to the roughing down process is heated just above the critical range, the grain structure of sheets is fine, but as the subsequent rolling is all done at temperatures below the critical range the effects are those of cold working. The grains are flattened and, due to the one-way rolling, much elongated; under the microscope they present a striated appearance, similar to that shown in photomicrograph No. 4, Fig. 260. This structure is commonly spoken of as the grain of the sheet. As a consequence of this working and resultant distortion of the grains, hot rolled sheets are hard and much less ductile transversely than longitudinally. Therefore, they bend best at a right angle to the direction of rolling. To make the sheet equally ductile in all directions, it would be necessary to replace this striated structure completely, a result not easily accomplished. One of the elements of this striated structure, the deformed grains, is eliminated by this annealing, and the refinement and restoration of these is accomplished only by heating the sheet to a temperature slightly above the critical range. Incidentally, the internal stresses are relieved and the ductility of the sheet is developed to the highest degree, fit to withstand very severe distortions, but it may still not be equally ductile in all directions because certain remnants of the deformed structure remain. Since the sheet is exposed to oxidizing gases throughout the process, it carries at the finish a fairly heavy coat of blue or bluish-black oxide. Hence, the process is frequently spoken of as **blue annealing.** Because of the loose scale produced and the tendency to deform the material, the process cannot be applied to the lighter gage sheets.

Box Annealing, sometimes referred to by the term close annealing, involves the use of annealing boxes for enclosing the sheets during the annealing operation. The essential equipment for box annealing consists of an annealing furnace, a sheet annealing box, and suitable apparatus for charging and drawing the box into and out of the furnace. The construction of annealing furnaces varies a great deal with their size and the kind of fuel available, but all types are of very simple design. Since the maximum temperatures attained in them are comparatively low and a reducing atmosphere is desired to prevent rapid oxidation and consequent destruction of the boxes, they are generally devoid of regenerators, recuperators or any other waste-heat appliances. They, therefore, consist essentially of but two parts, a combustion compartment, or a series of fire boxes in case coal is used, and a heating chamber. Gas fired furnaces are generally small, and may be either single or double. In the case of the single furnace, the heating chamber, which is large enough to admit but one box, hence about 16 ft. long, 8 ft. wide, and about 8 ft. high, is closed with a brick wall at one end and with swinging doors at the other and is covered with an arched roof. Externally the brick work is reinforced with steel stays and tie rods, assembled in the usual manner. The gas is admitted at the closed end into flue-like passages that extend along the bottom of each side of this heating chamber. Here, the gas, due to the lack of sufficient air for complete combustion, burns with a long smoky flame that reaches some distance into the heating chamber. The products of combustion are carried off through flues that lead to the stack located on top of the furnace. In coal fired furnaces, the longitudinal combustion flues are replaced by grates and fire boxes, usually three in number, which are distributed along one side of the heating chamber. The tops of these fire boxes are uncovered and on a level with the bottom of the furnace. The double furnaces are designed to receive two boxes, or charges, at once and side by side, hence are much larger than the single furnaces. The bottoms or floors of all sheet annealing furnaces are on the same level as the floor of the shop, in order to facilitate the charging and drawing of the boxes, which are large, heavy and unwieldly to handle.

The Annealing Box is made in two parts, a bottom and a top, or cover, both of heavy cast steel. The latter has the form of a rectangular hood, the length and width of which is but slightly greater than the corresponding dimensions of the largest sheet to be annealed. Inside, this hood is smooth, but, outside, it carries a number of heavy ribs, extending at right angles to each other over the top and around the sides to prevent its being warped and buckled by the repeated heating and cooling of many charges. Two lugs on each end, a little above the center of gravity, are also provided for handling the cover with a crane. The annealing bottom, or stand, describes a flat area on its upper side which is enclosed by a vertical rim some six or eight inches high and somewhat larger in length and width than the cover. On its under side three wide oval grooves, one along



Annealing Boxes and Double Annealing Furnace Ready for Charging.

each side and one along the center, extend the entire length of the bottom to serve as ball races for moving the charged box in and out of the furnace. When in use the bottom rests upon large steel balls, commonly known as cannon ball, which in turn rest in grooves, like those in the bottom, cut in heavy iron or steel slabs laid in the floor to form a runway into the furnace.

The Annealing Box in Use: The sheets are piled one upon another flat-wise for a height of four to five feet on this bottom, then the top is lowered over them upon the bottom, and the crevice formed between the top and the rim of the bottom is filled with very fine sand, thus effectually sealing off the contents of the box from the air. The box thus charged is pushed into the furnace, the doors closed and luted, and the temperature raised as rapidly as practicable until the outside of the box has attained a temperature equal to or a little above the predetermined annealing point. To obtain this result requires from 10 to 12 hours. As the temperature at the center of the pack is considerably below this point (200 to 250° F. lower) the dampers on the furnace are then partly closed and the fuel adjusted to hold this temperature while the pack is soaked for 4 to 6 hours longer. The box is then drawn and allowed to stand a specified length of time, which is calculated to permit the pack to cool to 200° F. or less. The boxes are usually charged and drawn with an overhead crane. For this purpose one end of a chain, which travels through a sheave anchored in front of the furnace, is attached to the hoist of the crane while the other is hooked to the bottom of the box for drawing, or to a push rod for charging. Temperatures, which were formerly judged by eye, are controlled by electrical pyrometers, usually of the thermo-electric type. In using an instrument of this type, the hot junction, thoroughly insulated, is placed in the middle of the pile, and the lead wires, also carefully insulated, are led down over one end of the pile through notches in the edge of the cover and thence to the potentiometer or other reading instrument.

Temperature Effects in Box Annealing: The objects in box annealing, of course, are to secure the benefits of annealing without the formation of scale on the surface of the sheets, but these objects cannot be attained to the degree of perfection sometimes desired. As the heating of the charge progresses, the air that is unavoidably trapped under the cover, expands and much of it escapes through the sand seal at the bottom. The oxygen in what remains probably reacts, at the lower temperatures, with the iron, leaving the atmosphere practically neutral. As the temperature of the box increases, occluded gases are given off by the steel and, eventually, as the temperature approaches 1400° F. a decarbonizing process, in which the carbon in the steel apparently reacts with oxides on the surface, sets in, so that a slight volume of combustible gases is continually being given off from the box. The deoxidizing process eventually

clears the sheet from scale or oxide, but when the box is drawn and cooling begins, these reactions cease, the gases contract, and air is sucked into the box through the sand seal. The oxygen of this air immediately scales the upper surface of the top sheet, which is put into a discard designated as top sheets, and also the edges of all the sheets in the charge. While the surface of the latter are not scaled, a strip from 2 to 3 inches in width bordering the edges on each side is discolored. This color ranges from a deep blue next to the edges to a light straw next the central area, which is perfectly clean and bright. This air can be excluded and the sheets kept bright and clear of oxide by introducing generous quantities of neutral or reducing gases under the cover while the box is cooling down, and this is often done to produce the so-called deoxidized steel. Needless to say, it adds somewhat to the cost of annealing.

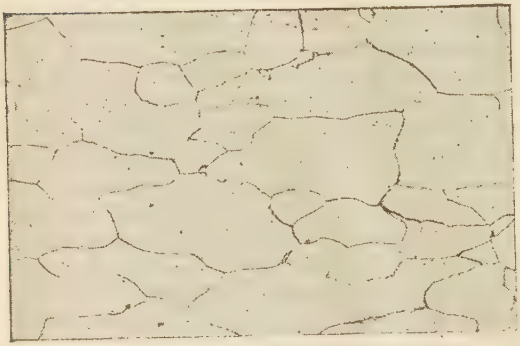
Limitations of Box Annealing: Again, since the sheets tend to become welded together if they are heated to a full annealing temperature, box annealing temperatures are seldom carried higher than 760° C. (1400° F.). This temperature is sufficient to eliminate the stresses and, to a great extent, the strains produced by the preceding rolling operations, and to develop the ductility almost to the maximum of which the steel is capable, but it causes sheets that have been pickled or pickled and cold rolled to stick together so firmly that the use of a sword is frequently necessary to loosen them. The maximum temperature to which a pickled and cold-rolled charge may be heated without fear of sticking the sheets is about 560° C. (1040° F.). While this temperature is high enough to relieve the rolling stresses, bring about a reformation of the grains, and soften the steel to a marked degree, it does not entirely efface the striated structure. Box annealing, therefore, cannot be used to produce material of highest ductility unless some special precautions are taken to prevent this sticking of the sheets. It is much to the credit of our sheet workers, therefore, that they are now producing even deep-drawing stock by cold rolling and box annealing methods, which give the bright, smooth, practically scale-free surface unobtainable in any other way. There is, also, another reason for not heating much beyond 760° C. (1400° F.) in the box annealing of sheets. While the best temperature for open annealing, to give the highest ductility and the maximum refinement of the grain is one just above the critical point, heating to the same temperature for box annealing tends to give an opposite effect; and the grains are very liable to become larger and cause the steel to be correspondingly less ductile and more brittle. This difference is to be attributed in part to the condition of strain and in part to the difference in the rates of cooling and heating in the two methods. In box annealing the steel would cool through the critical range of about 170° C., or 300° F., very slowly. Therefore, the passage of the ferrite, which is the principal component of steels of this grade, through its different phases, or allotropic forms, would be unhindered, and the crystalline matter resulting from each change

PHOTOMICROGRAPH No. 1

Structure of Sheet Bar. Carbon .10 per cent. Etched with nitric acid. Magnified 100 diameters.

PHOTOMICROGRAPH No. 2

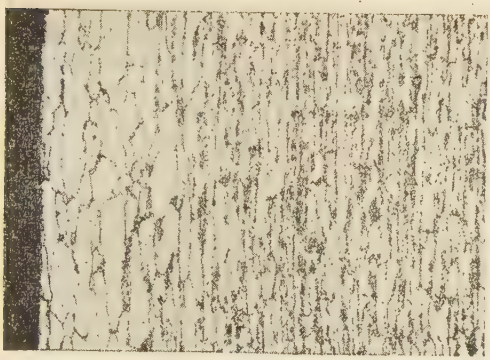
Structure of 24-gage sheet, as rolled on the sheet, or hot, mill. Edge of sheet parallel to direction of rolling. Carbon .07 per cent. Etched with nitric acid. Magnified 100 diameters.



PHOTOMICROGRAPH No. 3

Structure of 24-gage sheet after one pass cold rolled and box annealed dead soft. Edge of sheet parallel to direction of rolling. Carbon .06 per cent. Etched with nitric acid. Magnified 100 diameters. See Note 1 on opposite page.

FIG. 259. Photomicrographs showing effects upon the structure of the steel produced by the different processes used in manufacturing the lighter sheets. See note 2 on opposite page.



PHOTOMICROGRAPH No. 4

Structure of a 16-gage sheet, as rolled on the sheet, or hot, mill. Edge (surface to middle) of sheet parallel to direction of rolling. Carbon .11 per cent. Etched with nitric acid. Magnified 100 diameters.

PHOTOMICROGRAPH No. 5

Structure of 16-gage sheet. Blue annealed. Edge (surface to middle) of sheet parallel to direction of rolling. Carbon .11 per cent. Etched with nitric acid. Magnified 100 diameters.

NOTE 1. While the sheets represented by photomicrographs No. 2 and No. 3 are from the same heat, the micrographs are from different sheets, hence do not accurately indicate the carbon elimination that occurs on box annealing, which is usually equivalent to several points.

NOTE 2. These photomicrographs are intended only to illustrate the effects of the various processes specified, and the structures shown cannot be taken as typical of the products marketed under the commercial terms noted. The structures are affected somewhat by composition and finishing temperature, which in turn are varied according to the purpose for which the material is intended.

FIG. 260. Photomicrographs showing effects upon the structure of the steel produced by the different processes used in manufacturing the heavier sheets. See Note 2 above.

has time to reform crystals of large size. This matter is not so important in the case of very light gage sheets as with heavy ones, because the thinness of the former fixes narrow limits beyond which the crystals cannot grow. Also, if the grains of steel containing .10 per cent. of carbon have been only moderately deformed, box annealing at temperatures between 650° C. and 800° C. (1200° F. and 1475° F.), is liable to cause the grains to grow to very large size.

Another matter that requires careful attention is the variation in temperature at different points in the pack. The top is always hotter than the bottom, and if the charge is heated up rapidly, this difference may amount to as much as 200° F. However, with careful work this difference may be reduced to 50° F. or less.

Bluing and Polishing: Bluing has for its object the formation of a thin film of oxide upon the surface of the sheet that will act as a protective coating against atmospheric corrosion. So long as this coating remains unbroken and the sheet is not exposed to water and weathering processes, it is very efficient in preventing corrosion, but if the film is cracked, the rusting of the metal is hastened rather than retarded at these exposed points. The film is very brittle, but if it is even and thin it will permit considerable distortion of the sheet without breaking. Any forming, however, that distorts the sheet far beyond its elastic limit will certainly result in breaking the oxide film. The bluing may be effected by the use of either air or steam, applied to the sheets at certain temperatures considerably above atmospheric. In the case of large sheets steam is the usual agent, and is applied after the box annealing operation. After the charge has been drawn and allowed to cool to the proper temperature, the steam in proper quantity is introduced beneath the hood, or lid, of the box. After cooling to the proper temperature, the sheets are polished by passing them through the cold rolls.

Levelling: As the handling of the sheets during the various finishing operations generally results in distorting them somewhat, the final act in the preparation of plain flat sheets is levelling. There are two methods for carrying out this operation, namely, roller levelling and stretcher levelling. In the former, the sheets are fed singly into a machine consisting of two series, one above and one below, of small rolls, which are so arranged and adjusted as to bear on the sheet and force it through a series of curves thus flattening all elevations and depressions and straightening the bends. While this operation leaves the sheet flat enough for ordinary purposes, it cannot rectify any of the slight curvatures that are the result of the unavoidable irregularities of draft in rolling. To get the sheet perfectly flat it is necessary to stretcher level it. This operation is carried out by means of a hydraulic device known as a stretching machine. It consists of a hydraulic jack and a heavy level frame bearing two tracks on which are mounted the stretcher heads in the form of large clamps.

Fig. 261. View of Roller Leveller.

One of these can be adjusted to suit different lengths of sheets and made fast to the frame during the operation, while the other is attached to the jack, which is also anchored to the frame. In levelling, the ends of the sheet are securely held by the clamps while the jack is brought into action and the sheet is stretched to a point just beyond the elastic limit. The disappearance of all buckles in the sheet is taken as an indication that the stretching has progressed far enough. This operation renders the sheet perfectly flat. As the clamps deform the ends of the sheets, stretcher leveled sheets are usually resheared to correct dimensions after the leveling operation.

Inspection: Sheets that require only roller levelling are inspected as they are put into the levelling machine and counted as they leave it. An automatic counting machine is generally employed for the latter service. For the inspection, men of quick eye and long training are required to detect the minute defects that have escaped the eyes of those handling the sheets in previous operations. In the case of deep drawing stock, cupping tests and bending tests are made on at least each charge of sheets annealed, and appropriate physical tests for other grades of sheets are also employed. Some sheets are oiled to protect them from rusting in transit, and for this work a pair of felt rolls are employed as an attachment to the delivery end of the roller levelling machine. Stretcher levelled sheets are counted and inspected as they are crated or bundled for shipment.

Forming Operations: Since the manufacturers of sheets market a great deal of their product as roofing, ceiling, siding, metal lath, etc., the other finishing operations for black sheets consists of such forming operations as corrugating, crimping, pressing, stamping, punching, etc. Of these operations corrugating is the most widely used, as it increases the strength and stiffness of the sheet and adapts it to many uses, such as roofing, siding, flumes, culverts, etc. The load bearing strength of a

sheet is increased by corrugating from 9 to 12 times, depending upon the depth and width of the corrugations, which vary from ⅝ inch to 5 inches in width and from 5/32 inch to ⅞ inch in depth. There is a certain relation maintained between the width and depth of the corrugations. Thus, a 5-inch corrugation takes a depth of about ⅞ inch; a 3-inch, 9/16 inch; a 2½-inch, ½ inch, etc. The corrugations in the sheet may be either longitudinal or transverse, though the latter are seldom used. This work is done by passing the sheet cold through a set of corrugating rolls. These rolls are about 16 feet in length and about 28 inches in diameter and are each corrugated longitudinally. They are usually motor driven at a speed of not more than 2 r. p. m.

SECTION VI.

GALVANIZING, OR ZINC COATING.

Importance of Protecting Sheets from Corrosion: The ease and rapidity with which all forms of iron or steel rust or corrode in contact with water and oxygen or other corrosive substances occurring in the air make the inhibition or prevention of corrosion of vital interest to both manufacturers and consumers of sheets. On account of their thinness, sheets fail under corrosive action very quickly. A 20-gage sheet of plain carbon steel, for example, exposed to weathering and unprotected, could not be expected to last longer than a year in the Pittsburgh District; a copper bearing sheet would probably remain serviceable for 4 or 5 years longer. Up until the advent of copper bearing steel in 1912, the only practical means of arresting or preventing the corrosion of sheets was by protective coatings. These coatings may be classified as (1) Magnetic oxide coatings, (2) Paint coatings, (3) Vitreous Enamels, and (4) Metallic coatings. Metallic coatings for sheets may consist of pure metals, such as zinc and tin, or of an alloy of lead and tin, known as terne mixture. Of all these, zinc is the most extensively used because it is the cheapest metal available for the purpose, and, though not suitable for all kinds of work, affords protection for the metal over considerable periods of time under ordinary weathering conditions.

Nature of the Protection Afforded By the Zinc Coat: The process of applying a coating of zinc to iron or steel is called galvanizing, because the protective powers of the zinc were formerly attributed solely to the fact that iron and zinc are capable of forming a galvanic couple, in which the zinc forms an anode and the iron a cathode. The following illustration will serve to explain the full significance of this statement to those not familiar with the phenomena referred to by the terms employed. If a piece of iron or steel be immersed in a dilute solution of sulphuric acid, for example, the acid will immediately attack the iron, forming ferrous sulphate and hydrogen, thus: $Fe+H_2SO_4=FeSO_4+H_2$. Likewise, if a piece of commercial zinc be substituted for the iron or steel, a similar but much more violent action is obtained, and zinc passes into solution,

forming zinc sulphate as represented in the reaction, $Zn+H_2SO_4=ZnSO_4+H_2$. But if one end of the piece of zinc is brought into contact with one end of the piece of iron, or if the two metals are connected with a copper or iron wire, and the free ends are lowered into the acid, it is found that, while hydrogen is given off about the iron, only the zinc is attacked by the acid, and an electric current flows past the points in contact. Many other acids and salts could be substituted for the sulphuric acid with similar results, and the action is said to take place to a limited extent even with pure water. Furthermore, if a strip of zinc be lowered into a solution of ferrous sulphate, iron is displaced, and the zinc passes into solution, replacing the iron, thus: $Zn+FeSO_4=ZnSO_4+Fe$.

This change is explained by saying that the solution tension or pressure of zinc is higher than that of iron.

Factors that Affect the Life of the Zinc Coat: From these two facts, it will readily be seen that, so long as zinc remains in contact with the iron, the latter is protected from corrosion, but at the expense of the former. Indeed, the solution tension of zinc is so high that even the heaviest coatings would fail in a comparatively short time if this tendency of the zinc were not counteracted. Under ordinary atmospheric conditions a thin film of basic carbonate of zinc, or a mixture of zinc carbonate and zinc oxide, soon forms on the surface. This film, though it renders the bright sheet dull in appearance, is insoluble in water, and, therefore, acts as a protective coating to the zinc itself. It cannot, however, withstand the erosive forces of wind and rain, and the best zinc coat under weathering conditions must eventually give way. In an atmosphere carrying acid fumes, such as sulphur dioxide, for example, this protective film is destroyed, and the zinc coating corrodes very rapidly. Therefore, to protect the zinc coating and prolong the life of the sheet to its maximum, galvanized sheets should be painted as soon as the surface film has formed sufficiently to give a roughened surface to which the paint will adhere, Zinc also reacts with strong bases, such as potassium and sodium hydroxides. forming soluble zincates and hydrogen, thus,

$$Zn + 2NaOH=Na_2ZnO_2+H_2.$$

Hence, such substances as potash, lye, and quick lime, or mixtures containing these substances unneutralized, are very destructive to the coating of galvanized articles.

Method of Applying the Zinc Coat: While, in general, there are three methods of applying the zinc coat, only one, the hot dip process, is practicable for coating sheets. This method, the oldest of the three, was patented by Cranfurd in 1839 and by Morewood and Rogers in 1846. Essentially the process consisted of thoroughly cleaning the surface of the iron by pickling, then dipping the article into a bath of molten zinc covered with a layer of ammonium chloride (sal ammoniac). The article was allowed to remain in the bath until its temperature reached that of the

zinc, when, upon its removal, it was found to be completely covered or coated with the zinc. All this work was done by hand, and the apparatus was of the simplest form. In modern practice the galvanizing of sheets is carried out largely by machinery, but, though there has been much improvement in the method of applying the coating, the principles involved are the same. Virgin zinc, cast in blocks as it is reduced from the ore, is used and is known as spelter.

Physical Make-up and Composition of the Zinc Coat: The coating of zinc is not to be looked upon as a homogeneous layer of pure zinc. The coat consists of two more-or-less sharply defined layers of metal, namely, an outer layer of almost pure zinc of the same composition as the bath, and an inner thinner layer of iron-zinc alloy, of practically eutectic composition, but liable to be richer in zinc on the outside and richer in iron on the inner side next to the base metal. Details as to the structure of the coat are given in the section on hot galvanized wire (page 909). This alloy has a higher fusion temperature than zinc, and, therefore, crystallizes on the surface of the sheet. Some of these crystals become detached from the sheet, during the galvanizing process, and, being denser than the molten zinc, settle to the bottom of the galvanizing pot. Here the alloy collects with small amounts of certain other impurities to form a sediment which is technically known as dross, and must be periodically removed from the pot.

Importance of Uniformity and Continuity in the Coating: From what has been said concerning the nature of the protection afforded by zinc, it is apparent that this protection varies with the thickness of the coat. In practice, however, the thickness of the coating is expressed in ounces of spelter per square foot of sheet, and this weight is determined from the total weight of spelter consumed in coating a large number of sheets, such as the sheets coated during a run of a day or a week. Consequently, the durability of the sheet cannot be foretold from the weight of coat alone, for it also depends upon the uniformity and the continuity of the coat. For example, a sheet may carry, as a whole, the weight of coating specified, which in this case is, say, 2 oz., but if the zinc is so distributed that some parts carry 2½ oz. while other parts are covered to a depth corresponding to only 1½ oz., then the life of this sheet as a whole is only that of a sheet carrying a 1½-oz. coat. In the old days of hand dipping the variation in the thickness of the coat was liable to be much greater than this, and a variation of .35 oz. in a 2-oz. coat is considered good work even with machines. During the year 1915 the American Sheet and Tin Plate Company patented a device to carry on a process since known as flux finishing, by means of which they are able to apply a coating much more nearly uniform in thickness and of improved appearance. In bringing about this result, the invention has improved the lasting qualities of the sheets without increasing the total amount of zinc applied.

Thickness of Zinc Coatings: The thickest coat, however, is not suitable for all kinds of work, especially if the sheet has to be bent sharply, as in some forming operations. The heavier the coat the more liable it is to crack and peel off during the forming operations. For this reason, the thinnest coat is often the most desirable. Some argue that the heavier coat is always the best, because the zinc, due to its greater solution tension and electrolytic relation to iron, is able to protect the iron from corrosion, even if the coat is cracked and the iron laid bare. Proof of the correctness of this claim is supplied by the fact that the cut-off end of a galvanized wire or the sheared edge of a galvanized sheet will resist corrosion for long periods of time. However, as the cracking of a heavy coat by bending or working tends to cause the zinc to peel off and as such exposure of the iron stimulates electrolytic action, which accelerates the corrosion of the zinc, the coating retreats more or less rapidly away from the break. Then, since the zinc is capable of exerting this protective influence over a very limited area or zone, the iron at the break will eventually be exposed to uninhibited corrosion, when it will fail very quickly. This, and other reasons pertaining to economy as well as adaptability, makes it highly desirable to produce sheets carrying different thicknesses of coat. Formerly, it was a difficult matter to produce a coat of predetermined weight. Modern methods, however, make it possible not only to produce relatively uniformly coated sheets but also to control the thickness of the coat very nicely.

Preliminaries to the Galvanizing Process: The modern process for galvanizing sheets requires three days or more of continuous treatment. After the completion of the hot rolling, the sheet, if lighter than 16 gage, is next given one pass through the cold rolls to flatten it and remove all marks of the opening operation, and is then box annealed. Sheets or plates heavier than 16 gage are generally open annealed and roller levelled while hot. In the case of the light sheets, these two operations usually occupy about 24 hours. As soon as the sheets have cooled after the annealing operation, they are transported to the pickling department, placed in a loose bundle upon a rack or crate and lowered into the vat of the pickling machine, which is generally of the surging, or displacement agitator, type. The acid is diluted to about 7 per cent., the temperature is kept between 140° F. and 200° F., depending on the grade of steel, and the time of pickling is from 15 to 20 minutes. The sheets are left in the acid bath no longer than is necessary to remove all the scale, as over-pickling is to be carefully guarded against. Over-pickling is wasteful of acid, increases the pickling loss on the sheet, and may actually do harm to the steel. Over-pickling is indicated as soon as the grain structure of the steel begins to become visible on the surface of the sheet. As soon as the sheets have been freed from scale, they are lifted out of the pickle and lowered into another tank containing fresh water. This treatment partially removes the acid salts and detaches the small particles of dirt that cling to their surfaces when

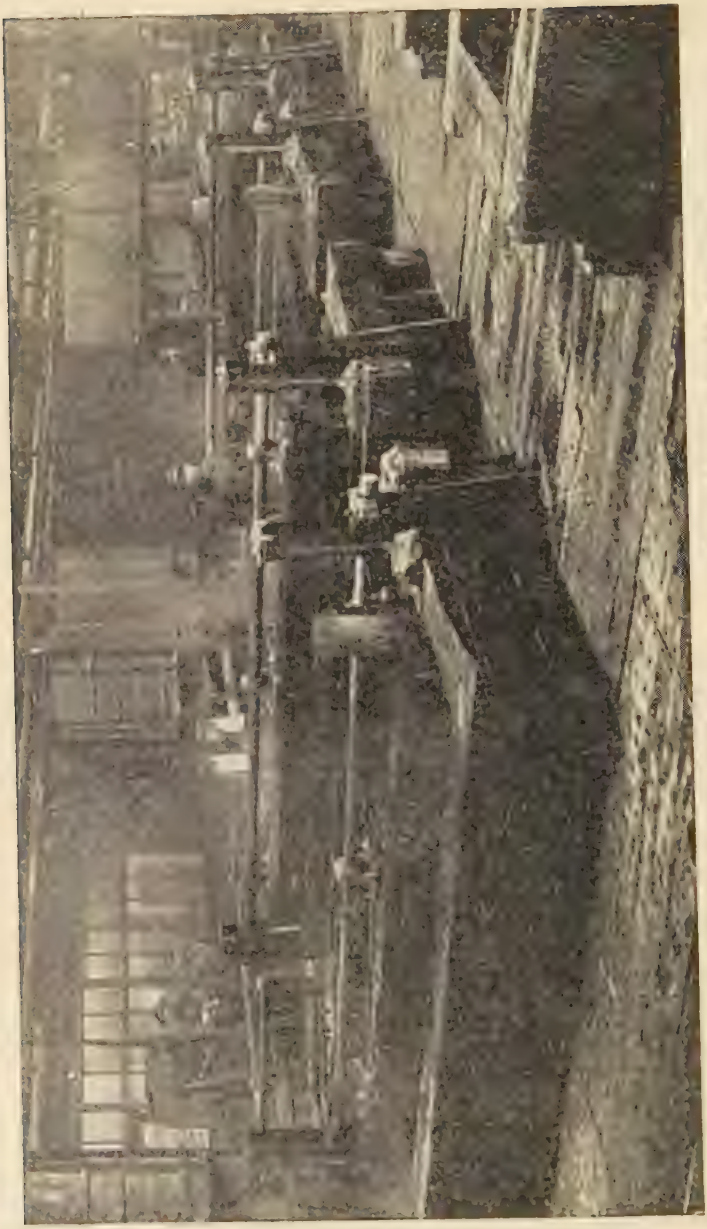


Fig. 262. Pickling Machines for Galvanizing. Surging Type.

the sheets are removed from the pickle. This done, the sheets are immediately placed in a bosh of water, where they remain immersed until removed for the galvanizing process. In most plants, the sheets are left thus in the boshes for 24 hours or more in order to allow the absorbed hydrogen plenty of time to escape.

The Modern Method of Galvanizing Sheets: Following these preliminary treatments, the sheets are taken in bundles to the galvanizing department. Here each sheet singly must pass through a series of operations, which, by the use of mechanical devices, are made continuous. In ordinary practice, these operations consist of galvanizing, cooling, and levelling. Each operation requires a special apparatus, but these apparatus are closely connected to form a single unit, which will now be described somewhat in detail.

The Galvanizing Pot: The central figure in this unit is the galvanizing pot. It is made up of three principal parts, namely, a rectangular tank-like kettle for containing the molten zinc, a furnace or setting of brick for heating this kettle, and a galvanizing machine which sits in the kettle and draws the sheets through the bath of molten zinc. Both the kettle and the machine are made of low carbon basic open hearth steel,

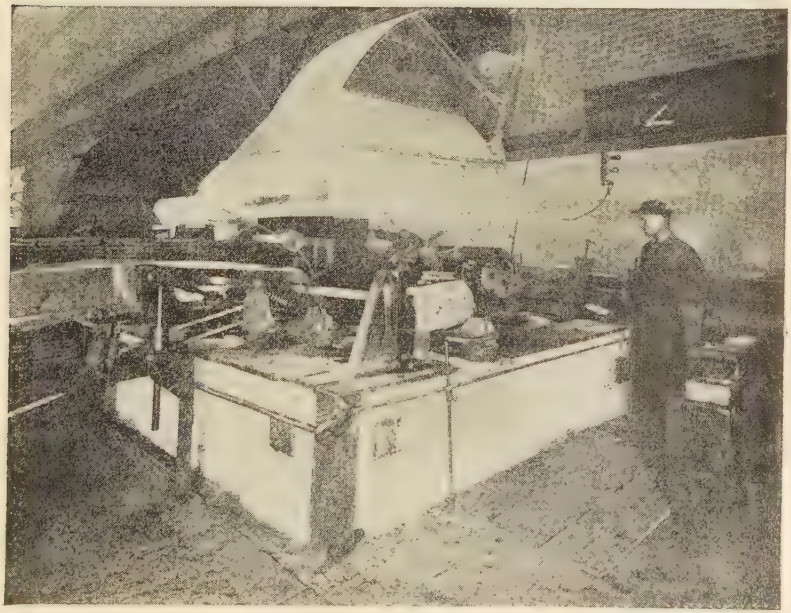


FIG. 263. Galvanizing Assembly, Showing Furnace with Pot and Machine in Position for Galvanizing.

as it has been found, after years of experimentation, in which every kind of material it was practicable to use for these purposes was tried, that this material resists the alloying action of the zinc better than any other. For the construction of the kettle, plates from ¾ inch to 1½ inches thick are employed, and these are riveted or, preferably, welded together. The kettles vary in size according to the width and thickness of the sheets they are designed to galvanize, the range in dimensions being from 6 to 15 feet in length, 3 to 6 feet in width, and 2½ to 5 feet in depth. They have an operating capacity of from 60,000 to 150,000 pounds of spelter. They are each set upon a foundation of brick work, which covers the entire bottom and frequently extends up about the sides and ends for a height of about eight inches. In order to resist the fluid pressure of the molten zinc, they must be generously supported from the outside. This reinforcing is usually accomplished at the top and bottom by flanging the plates themselves or by rivetting on a rim of angles, and, if the kettle is a deep one, it is, also, reinforced in the middle by a cast iron brace, belting the kettle horizontally. The kettles are usually set so that their tops are from 3 to 4 feet above the level of the shop floor.

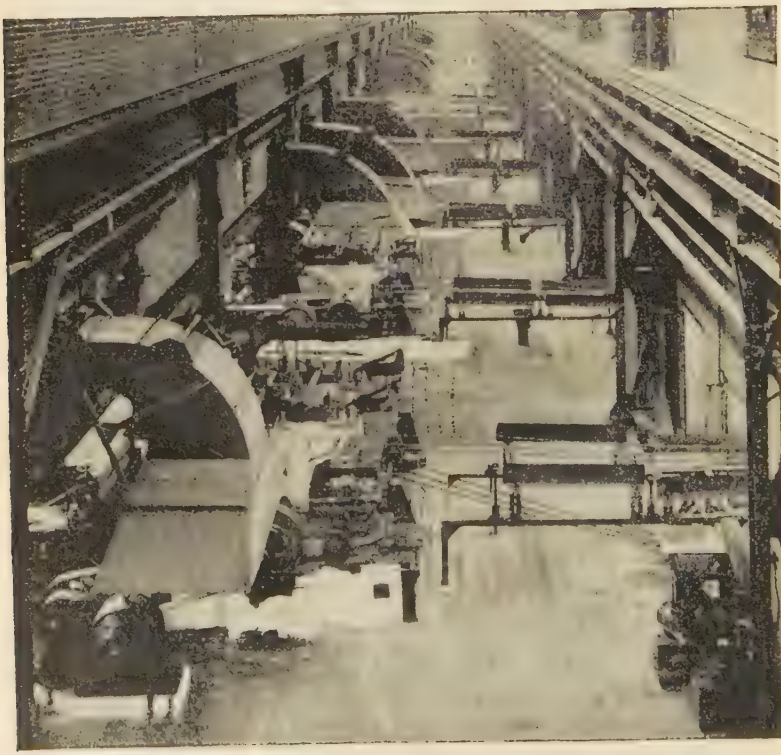


Fig. 264. View of Modern Galvanizing Room. Note Hoods over Pots to carry off Fumes.

The Design of the Furnace, or heating chamber, depends upon the fuel used. Formerly, coke was the fuel almost universally used, and with it the construction of the heating chamber was very simple. After the kettle was placed upon its foundation, a setting of brick work was built up around it, leaving a space, the width of which was from 8 to 16 inches, depending upon the heat required, between the sides of the kettle and the setting, for the fire. Holes were left in the brick work near the bottom of this space to admit air to the coke, and the top of the space was partially covered with plates, by means of which the draft was regulated and the temperature controlled. In the majority of plants, however, soft coal is the cheapest fuel. With this fuel, a grate or fire box is placed at one end of the kettle, and the space left about the kettle is bricked up tight and covered to form flues for conducting the hot gases along the sides of the kettle and thence to a chimney or a stack, which is usually built large enough to serve several pots. In general, the arrangement of all flues, grates, or burners, must be such that no part of the kettle not covered with zinc on the inside shall be exposed to flame or hot gases on the outside. Recently, some plants have turned to gaseous fuels. By bricking over the top of the firing space in the coke-fired bath, leaving openings here and there for the escape of the products of combustion, and introducing the gas through proper burners at the bottom, it was found that the cost of firing with gas compared favorably with coke, with the advantage that the gas required no handling and made it easier to control the temperature. After the pot has been fired and made ready for operation, the amount of fuel depends upon the weight of steel coated and the amount of zinc consumed, other conditions being normal.

The Galvanizing Machine, sometimes spoken of as a rigging, consists of a flux box, three sets of rolls about 7 inches in diameter, gearing for driving the rolls, a system of guides between the rolls, and a T-shaped frame of plates bolted and rivetted together for supporting all these devices. A photograph of this machine is shown in Fig. 265. The first set of rolls, or entering rolls, are supported at one end of the table of the T formed by the frame and just above the flux box. They lie in a plane at such an angle to the horizontal that they will grasp the sheet and force it downward through the flux box and beneath the surface of the molten zinc. The flux box, made of steel plates, has the form of a rectangular box without top or bottom, and is about 10 inches deep, 12 inches wide, and long enough to bridge the distance between the two sides of the frame, which support it at such a height that its lower edge will extend into the molten zinc a distance of about 3 inches, with the metal at its lowest operating level. The second set of rolls, or the middle rolls, lie at the bottom of a slot coincident with the vertical axis of the upright stem of the T. They, of course, lie one above the other in a vertical plane. The last, or exit, rolls are located on the other end of the table of the T, and lie in a horizontal plane almost coincident with the surface of the molten zinc. The

two rolls in each set are geared together by means of wrought steel pinions, and are motor driven by means of worm gears mounted on the opposite end of one of the rolls. The space between these sets of rolls is bridged, both above and below, with guides, so that the sheet cannot leave its course. This machine is bodily lowered into and lifted out of the kettle with an overhead crane, whenever it becomes necessary or desirable to make repairs to the kettle or machine or to cease operating the pot for more than a few hours.

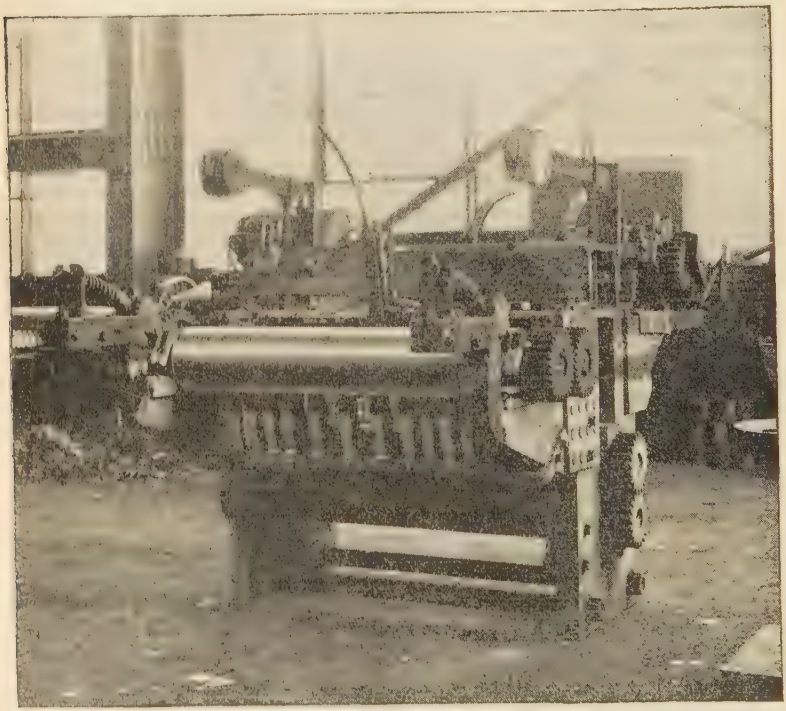


Fig. 265. Galvanizing Machine.

The Leveller is of the ordinary roller type, and feeds directly upon a table, from which the sheet may be pushed directly upon a "porcupine" cooling rack, as shown in Fig. 266. This rack is of the revolving type. The central portion consists of a steel cylinder, or pipe, about 10 inches in diameter and 15 feet in length, mounted horizontally, with its axis on the same level as the table top, upon two cast iron supports, which furnish bearings for the two small axles that project from each end. Projecting radially from this central portion to a distance of thirty inches or more,

are a great number of half-inch steel rods, or fingers, which are arranged horizontally in parallel rows about one inch apart at the base, thus giving the upper semi-circumference of the rack a holding capacity of 15 to 20 sheets. By revolving the rack, the sheets are lifted from the level of the table through an arc of 180° to the same level on the opposite side, and as the rack is revolved only fast enough to take the sheets as they come from the galvanizing pot, they generally have plenty of time to cool to, or almost to, atmospheric temperatures in this interval. With the exception of a trimming shear, which is often required to trim sheets requiring closer cutting than can be done on the hot mill shears; a corrugating machine, which has already been described; and the necessary trucks or cranes for transporting the sheets, this description includes all the equipment required in general galvanizing practice, but does not include a great deal of apparatus needed for carrying on special operations necessary to the supplementary processes employed by some manufacturers.

Fig. 266. Porcupine Cooling Rack for Galvanized Sheets.

Firing a New Pot: With the new kettle properly set and all the essential apparatus in readiness, the firing of the new pot is begun. Before galvanizing operations can begin, however, enough spelter to fill the kettle to the proper depth must be melted down. This initial melt must be made with due care, else the kettle will be injured or possibly ruined. As lead is much heavier than spelter, has a much lower melting point, and does not mix or alloy with zinc or iron, a quantity sufficient to cover the bottom of the kettle to a depth of 6 or 8 inches is generally added first. When molten, this lead forms a cushion that protects the bottom from

the zinc during the melting down period, and, later, during operations, from the dross that collects there. Upon this lead the flat pigs of spelter are piled so that those next to the sides of the kettle will lie on edge with their broadest faces against the steel plates, and as these melt others will slide down toward the sides to take their places. With the kettle properly filled the fire is started carefully and the kettle very gradually and evenly heated. If any part of the kettle should be heated much above the melting point of the spelter, which is only 420° C., and should then come into contact with the spelter, the iron would rapidly alloy with the zinc, forming a weak spot that might cause the kettle to fail very early. It requires close watching on the part of the operator and from 30 to 40 hours' time, depending upon the size of the pot, to melt down the full charge in a new kettle; any carelessness on the part of the operator or an attempt to hurry the work may result in a burnt-out kettle even before galvanizing operations begin.

Final Preparations: A great deal of zinc oxide, commercially known as zinc ashes, results from the melting down of the spelter, and, being lighter than the metal, floats on the top of the bath. These ashes must now be removed by skimming before galvanizing operations may begin. As considerable spelter may become entangled with the ashes in the operation, the skimming must be done with care to prevent wasting this spelter. Therefore, in order to increase the fluidity of the spelter on the surface and bring about a better separation of ashes and spelter, a little white sal ammoniac is first scattered over the surface of the bath, when the ashes may be raked to one side and removed with a shallow ladle-like skimmer bearing several small perforations in the bottom. Instead of the sal ammoniac, some operators sprinkle resin over the bath, which is then ignited just before skimming. The burning of the resin heats the top of the bath and causes the zinc to separate nicely. The zinc ashes are saved to be returned to the zinc smelter or sold to paint manufacturers. As soon as the ashes have been removed, more sal ammoniac is sprinkled upon the bath until the surface is well covered and the spelter protected from further surface oxidation. This done, the galvanizing machine, which has been well warmed up, may be lowered slowly and cautiously into the bath. If no other means are available, this warming may be accomplished by suspending the machine over the hot bath for an hour or two. The exit rolls, however, require special attention. They must be carefully cleaned and pickled, then preheated in a bath of molten lead just prior to being placed into the zinc bath. Here, as soon as the machine can be set in motion, they are sprinkled with flux until they become evenly coated with the zinc, showing a clean metallic surface. In the meantime, a small tank containing a dilute solution of muriatic acid, and all the other apparatus has been gotten ready and connected up in their proper places in the series. As soon as the galvanizing machine is in place, the flux box is filled by carefully adding sal ammoniac, a few pounds at a time.

The Galvanizing Operations: With this equipment, the galvanizing of the sheets is entirely mechanical. Each of the pickled and washed sheets is immersed for a few seconds in the muriatic acid bath, then started, at a speed of 40 to 70 feet per minute, through the entering rolls, which carry it through the flux box, to the middle rolls. These rolls force it through guides to the exit rolls, which propel it out upon the transfer table, where it continues without hesitation onward through the leveller to an inspection table. Here, it is inspected on one side and pushed by hand upon the cooling rack, which carries it slowly over to a position diametrically opposite, where it can be removed, now quite cold and with the other side up for inspection, and placed upon a truck. The speed varies according to the kind of coat, the gage of the sheet, and the heating facilities of the pot, so no definite figure for output can be given. However, it may be stated that a pot, to be considered as efficiently operated, should turn out a minimum of 60,000 linear feet of sheets, 20 gage and lighter and carrying the ordinary coating, each day of 24 hours.

Functions of the Acid and Flux: The function of the hydrochloric acid is to remove all traces of oxide or rust that may have formed on the sheet during the washing, neutralizing and soaking that follow the pickling with sulphuric acid. Treatment with hydrochloric acid leaves the surfaces of the sheet covered with a film of water bearing both hydrochloric acid and ferrous chloride in solution. Before the sheet enters the molten zinc bath to be galvanized, it must be thoroughly dried and cleansed of both acid and salts, out of contact with the air, and this is the principal function of the flux contained in the flux box. Rubber rolls are sometimes employed to squeeze off the excess acid, but these leave the surfaces of the sheet covered with a film of the solution which protects it from the air during the short journey through these rolls to the flux box. As the sheet enters the fused sal ammoniac, the last trace of this solution is vaporized, and the sheet enters the zinc bath perfectly dry and clean. The flux evidently has other important functions to perform, also. Various substitutes, for the sal ammoniac, both alkaline and neutral in character, have been tried, but, with one exception, these have failed to give satisfactory results. Zinc ammonium chloride has been used successfully, but it is no cheaper than the sal ammoniac and is of the same character, chemically. No special advantage, aside from the fact that it gives no fumes, can be claimed for it.

Purpose of the Rolls and Succeeding Apparatus: The function of the middle rolls is merely to propel the sheet onward until it can be grasped by the exit rolls. These last rolls play a most important part in the process, as they constitute one of the means whereby the thickness of the coat is controlled and its uniformity maintained. Upon entering the zinc bath from the flux box, the sheet soon becomes heated to the temperature of fusion for zinc, when this element begins to alloy with the iron. The sheet should now be withdrawn from the bath as quickly as possible in order that this alloy coat will be of minimum thickness. This withdrawal is

made through the exit rolls, which tend to strip off the excess zinc that adheres to the sheet and to distribute the remainder evenly over the surface. Evidently this stripping action of the exit rolls depends upon the height of metal relative to the centers of the rolls, becoming zero when the surface of the molten spelter rises above the nip. As the sheet rises from the exit rolls it is bent forward by a guide and falls upon the chain conveyor, which carries it to the leveller.

Factors Affecting the Appearance of the Coating: As the sheet issues from the tank, it presents to view a plain, rather dull, metallic surface, but by the time it has been deposited upon the conveyor the zinc has begun to crystallize, and the sheet rapidly takes on a bright spangled appearance. The size of these spangles is a matter of concern, because the larger and more uniform in size the spangle is, the brighter, cleaner, and more pleasing in appearance is the sheet. There is no evidence that the size of the spangle is in any way indicative of the quality of the coating. Two successive sheets sent through the pot in exactly the same way may show spangles widely differing in size. Furthermore, the galvanizer has little or no control over the size of the spangle. The spangle can be prevented from forming by plunging the hot coated sheet into cold water, when it will retain much the same appearance it has on leaving the bath. Tin added to the spelter in small quantities is said to improve the appearance of the sheet in this respect. With undoctored spelter, however, the size of the spangle appears to be a function or property of the steel base. When the spangle is very small or very uneven, the sheet is classed as a gray sheet, and is discarded. The base metal of gray sheets is always very porous, as shown by the fact that it is permeable to hydrogen. It also shows evidence of overoxidation, so that some reputable students are inclined to attribute this defect mainly to oxides in the steel. From observation, it is evident that each spangle is the result of a single crystallizing activity which springs from a single nucleus, and upon the number of these nuclei depends the size of the spangles. These nuclei may be caused to form by external influences, by solid particles in the spelter, or by disturbing influences in the steel. The fact that, if external influences be removed, both large and small spangles may be obtained from the same spelter, and even on the same sheet points to the steel base as the chief factor in determining the size of the spangle.

Factors Affecting the Thickness of the Coat: Since the coat is made up of two layers of metal, it may be well to consider the factors that affect the thickness of each separately. The thickness of the outer coat, or the zinc coat, depends upon the temperature of the zinc and the temperature of the base metal as the sheet leaves the bath and the stripping effect of the exit rolls. As the base metal derives its heat from the zinc, its temperature will depend on that of the zinc, the gage of the sheet, and the speed with which it passes through the machine. If the temperature of the zinc is kept constant and the speed regulated so that the sheet is

heated to the same temperature just before it reaches the exit rolls, then the thickness of the coat depends on the stripping effect of the rolls entirely. As already stated, this stripping effect depends on the design of the rolls and their distance above the zinc level. The alloy coat, being more brittle than the zinc, must be kept as thin as possible if the sheet is to be subjected to deforming operations. As iron and zinc do not begin to alloy until both are heated beyond the fusion point of zinc, no alloy coat is formed until this temperature is attained by the sheet, after which time the thickness of the alloy coat will depend upon the temperature of the zinc and the length of time the sheet remains in contact with it. For a thin coat, therefore, the sheet should reach this temperature just as it is being withdrawn from the bath. For special thin coat, known as tight coat, the proper conditions are obtained in part by filling the kettle to the level of the bottom of the flux box with lead, and the remainder of the kettle with zinc. In passing through this bath, the sheet is preheated by the lead and is in contact with the zinc but a very short time. Coating applied in this way is sometimes referred to as lead and zinc coat. Tight coats are difficult to apply, and the output of the machine is only about half normal.

Care of the Pot: From what has been said, it is evident that the successful and efficient operation of the galvanizing pot requires the closest care and attention and depends largely upon the equipment and the experience and skill of the operator. The kettle must be properly fired, the rolls kept in good working order, the zinc level maintained at the designated level, the flux kept in good condition, the dross removed at proper intervals, and all the auxiliary equipment kept running smoothly. Needless to say, instructions covering all details of the operation of the pot are out of the question here, but a few remarks concerning some of these matters may be found profitable.

Flux Skimmings: As some of the sal ammoniac sublimes during the operation of the kettle, new flux must be added from time to time, both to the flux box and on top of the metal. After a kettle has been in operation for some time, however, the flux, through the absorption of zinc and iron oxides and chlorides, becomes so viscous and dirty that it is no longer useful for galvanizing purposes and must be skimmed off. This skimming is done with a ladle bearing a great number of perforations, about ¼ inch in diameter, through which any free metal spooned up may drop back into the bath. In spite of precautions, some zinc is wasted in removing the skimmings. In some plants, these skimmings are remelted to recover this entangled zinc then sold to chemical manufacturers who purify and recover the salts, but in some other plants, the entangled zinc is dissolved with hydrochloric acid and the resultant mixture of zinc and ammonium chlorides is sold to tin mills, as it makes an excellent tinning flux. The flux must also be removed before a machine is taken out for repairs or on

account of a shut down, and for the removal of the dross. At such times, if the flux is in good condition, it is saved, broken up when cold and used again.

Removal of the Dross: The alloy of zinc and iron that becomes detached from the sheets, or forms from the action of the zinc upon the kettle and the machine itself, sinks to the bottom of the zinc bath, where it accumulates like a sediment in a pond of water. The action of the rolls in drawing the sheets through the bath tends to keep up an agitation that prevents this dross from solidifying. The dross apparently carries some flux down with it, for it is rich in chlorides, which make it somewhat corrosive. Hence the desirability of protecting the bottom of the kettle with the cushion of lead. It represents a serious source of zinc waste, as frequently 10 per cent. of the zinc is lost in this way. It, therefore, accumulates rather rapidly, and since it ruins the coat of any sheet it comes in contact with, it must be removed at intervals to prevent the accumulation from interfering with the work. This removal is generally effected with a perforated dross scoop after skimming off the flux. In some plants, a tube about 12 inches in diameter, is let down into the bath vertically so that its lower end rests just at the bottom of the layer of dross. By dipping out the zinc inside this tube, the dross itself is forced up into the tube, and may be dipped out. The dross is cast in molds or pans to form pigs, and sold to be refined and utilized in the manufacture of brass. These facts explain why galvanizing kettles are never heated at the bottom. A fire under the bottom would continually boil the dross up against the sheets and would also be destructive to the bottom itself. Without a fire under the bottom, the dross can settle and remain undisturbed until it is removed.

The Life of a Kettle is somewhat uncertain even in careful and skillful hands; in careless hands, it may last but a few days or weeks. When operated with care and intelligence, they may last from 10 to 18 months or even longer. Reserve kettles, therefore, must be kept on hand. The kettle usually fails through springing a leak, letting the molten spelter spurt out into the flues or the fire. If the leak is a small one, not in a seam, and the kettle is otherwise in good condition, it may be patched, but generally it is best to replace such a kettle with a new one. In any case, on the discovery of a leak, galvanizing operations should cease and due preparations made for saving the zinc remaining in the kettle.

CHAPTER IV.

MANUFACTURE OF TIN PLATE MILL PRODUCTS.

SECTION I.

NATURE, USES AND HISTORY OF TIN PLATE.

Tin Plate: Since tin plate is a word not fully descriptive of the material it represents, and has frequently been misinterpreted, it may be well to explain here, for the benefit of any who may be just beginning the study of the subject, that a tin plate is a sheet of steel or wrought iron that has been coated with tin. Tin, itself, is soft and malleable, possesses little strength, and is comparatively expensive, being worth about ten times as much as wrought iron or steel. Hence the statement, heard often, that a certain utensil, for example, is made from pure block tin is misleading, for the articles ordinarily known as tinware are never made from pure tin, because tin alone is not hard or strong enough to withstand the usage such articles are put to. This use of the term tin plate can be attributed to, and is justified by, the fact that the coating of one metal by another has always been referred to as plating. Thus, we have gold-plated, silver-plated, nickel-plated ware, etc. Hence, it appears entirely appropriate to apply the term tin plate to a sheet of iron or steel coated with tin. Sheets of solid tin are designated as sheet tin.

Method of Applying the Tin Coat: From the beginning, the process for applying the tin coat has remained one and the same, and may be described as a hot-dip process similar to the process for galvanizing that bears the same name. As in the case of hot galvanizing, the surface of the sheet must be perfectly free from dirt, grease, oxide, moisture, or other foreign matter, so that it will present a clean metallic surface of iron to the molten tin. Under these conditions, as soon as the iron becomes heated to the melting point of the tin, the latter will alloy with the former. Then, as the sheet is withdrawn from the bath of molten metal, enough tin adheres to the surface to form a coat of pure tin on the outside, which soon solidifies.

Value of the Tin Coat: Since this outer coat is bonded to the iron by the alloy coat beneath, it adheres very firmly to the iron, and since tin is a very soft metal, the sheet or plate may be pressed, stamped or bent into almost any form without causing the coat to break or peel off, if the plate has been properly coated. Added to this advantage, tin presents other properties that make it almost the ideal coating for sheets of steel or iron. Being a white, lustrous metal that scarcely tarnishes

in the air, it makes a sheet of lasting beauty. As it has a low melting point and does not readily oxidize in the air, iron or steel coated with it can be easily soldered. Since it is capable of withstanding all the ordinary atmospheric agents that cause iron to corrode so rapidly, it acts as a protector to the iron or steel which it covers. But all these desirable qualities of the tin could be realized to but a limited extent, if the tin were not reinforced by the iron or steel beneath, which supplies those tensile properties lacking in the tin. Hence, in a tin plate, we have united the properties of two metals in a combination that is a near approach to that ideal metal nature has failed to provide.

Nature of the Protection Afforded the Iron by the Tin: The coating of tin will retain its luster and protect the iron from corrosion perfectly so long as the continuity of the coat remains unaffected, but it is a well known fact that, once the coating of tin is broken, exposing the iron, the corrosion of the latter goes on more rapidly than if the tin were absent. In the light of the electrolytic theory of corrosion of iron, this phenomenon is explained by the fact that tin is capable of forming a cathode with iron. Hence, in the presence of any corrosive substance at any place or point not covered by the coat, iron is dissolved in preference to the tin, for even if the tin should dissolve, the iron would tend to replace it in the solution, and the tin would be reduced to the metallic state. Furthermore, in the presence of water or moisture carrying the least trace of impurity in solution, the two metals will form an electrolytic couple, and a localized electrolytic action will take place. As the iron forms the anode of this couple, it is this metal that is acted upon by the negative ions, and so passes into solution, while tin, coming into contact only with positively charged ions, remains unacted upon. The fact that tin itself resists corrosion so well is explained by the fact that its solution tension is very low.

Use for Food Containers: This tension is so low that tin will resist the action of dilute acids, hydrochloric acid being the only one that may be said to dissolve it rapidly. This fact led experimenters, early in the nineteenth century, to try tin plate as a food container. At first, although it could be shown that tin resists the action of fruit and vegetable juices so well that the thinnest coat of tin would be sufficient to preserve the foodstuff for years, there was much loss from spoilage. This spoilage was at first attributed to the tin plate, but in 1895 the discovery was made that it was due largely to bacteria in the air that were not excluded or destroyed by the methods of canning then followed. It has also been found that some spoilage could be attributed to minute areas or points in the surface of the sheet that were not covered by the tin. These uncoated spots are too small to be detected by the naked eye, and are known as pin holes, or pores. It appears that their total elimination is very difficult to accomplish, the more so because no practical means of detecting their presence in the tin plate has been discovered. However, improved

methods of manufacture have reduced the number of these pin holes to a minimum, and improvements in the method of processing and canning have practically eliminated spoilage due to bacteria, so that tin plate canning has now become the chief means of conserving as well as preserving foodstuffs. Some idea as to the relation of tin plate to the conservation of food can be formed from the fact that approximately 8,000,000,000 tin cans of various sizes are now consumed annually by the food packing industries.

Thickness of the Coat: From the facts noted in the preceding paragraph, it would appear that even the thinnest coating of tin, if perfectly distributed, may suffice to protect the iron for a long time; but that, if the coating is imperfect, exposing the iron, it can afford no protection at the point of exposure no matter how heavy the coat may be or how small the perforation. This statement is substantiated both by common experience and by results from experiments conducted by many investigators. Thus, for example, it has been shown that there are liable to be as many pin holes, as revealed by the gelatine test[1], in a plate carrying a three-pound coat as in one carrying only a one-pound coat, which is thinner than the lightest coat it is, industrially, possible to apply. Furthermore, while there is a tendency for more heavily coated tin cans to develop fewer perforations after canning than the lightly coated ones, the actual number of such perforations bears very little relation to the weight of the coating and no relation to the number of pin holes indicated by the gelatine test, except that the actual perforations are always fewer in number than the pin holes indicated by the test[2]. In canning, it was found that a slight reaction between the tin and the vegetables and fruit juices takes place and that this reaction destroys the coloring of the foods. As the use of artificial coloring is prohibited by law, this difficulty is overcome by using as little tin as possible and coating the inside of the can with a hard lacquer.

Occurrence of Tin: Another reason why no more tin should be used than is necessary is the scarcity of tin itself. From a commercial standpoint, tin is one of the rare and precious metals. It occurs in nature both as the sulphide and the oxide, SnO_2; the latter, which is known as cassiterite, or tin stone, forms the only ore of tin. It was formerly found in large quantities in the South of England and in smaller quantities on the continent of Europe, but these mines, after having been worked for 3000 years or more, are now almost exhausted. Today the world's supply of tin is obtained chiefly from deposits found on the Malay Peninsula, the Island of Banca, Australia, and the State of Bolivia, S. A. Most of the tin

[1]For details of this test see "The Electrolytic Theory of the Corrosion of Iron and Steel and its Application," by W. H. Walker, Jour. (British) Iron and Steel Institute, 1909.

[2]From a report of an Investigation by a Technical Committee Representing the National Canners Association, the American Sheet and Tin Plate Company, and the American Can Company.

consumed in this country comes from the Malay District, and is known as "Straits Tin." All these sources of supply are under the control of citizens of other countries, and the pig, or block, tin market is held very closely, so that, as the consumption of tin increases, the price increases, also, and usually in geometrical ratio. The metallurgy of tin involves roasting of the ore to drive off sulphur and arsenic; treatment with hydrochloric acid to dissolve iron, copper and other metals; washing with water to remove soluble substances; heating the refined ore in a reverberatory furnace with coal to reduce the oxide; and a final purification of the metallic tin by remelting it at a low temperature.

Grades of Tin Plate: For certain purposes, however, the heavier coatings are to be preferred. This statement applies particularly to tin plate that is to be made into utensils which are subjected to considerable wear from cleaning, scouring, or polishing. A heavy coat also adds to the appearance of the sheet. A certain amount of tin is required to cover up completely the minute surface inequalities of the base metal, in the presence of which that smooth, lustrous, mirror-like surface so much desired for some work is impossible. Therefore, tin plate is now manufactured in about ten different qualities or finishes, which are graded according to the amount of tin they carry. Following the old English custom, however, these different finishes are put into two main grades, or divisions, and are known as coke tin plate and charcoal tin plate. As will be explained later, these terms originally were descriptive of the base metal, but now they denote only finish. Some manufacturers make as many as five different grades of coke plate and six different grades of charcoal, each designated by an individual brand, letter, or name. As a rule, coke plate carries a coating of from 1.5 to 2.5 pounds of tin per base box while charcoal plate carries from 3 to 7 pounds. As to gage, most coke plates are made to average 95 lb. per base box, but some are as heavy as 128 lb. and some as light as 55 lb. Charcoal plates are, as a rule, heavier than cokes, most of them falling within the range of 107 lb. (IC) to 235 lb. (6X). Taggers tin, weighing 55, 60, and 65 lb. per base box, is made in both coke and charcoal grades.

The Allotropic Properties of Tin must be considered in the utilization of tin plate, or any alloy containing tin, for certain purposes. While tin at ordinary temperatures is very soft and malleable, at about 200° C. (392° F.), it becomes very brittle and will break if subjected to slight bending, and crumble if hammered. Again, the soft, malleable, crystalline form is stable only at temperatures above 20° C. (68° F.). Between 20° C. and —48° or —50° C. (—58° F.), it gradually changes into an amorphous form so brittle and fragile that it can be powdered between the fingers. The rapidity of the change apparently increases as the temperature decreases. At —48° C. it takes place rapidly, while at —19° C., or about 0° F., several days or a few weeks may be required to bring it about.

Vibration apparently accelerates the change. In this country tin in this form is commonly known as "sick tin," while in Russia, where it is more common, the phenomenon is referred to as the "tin pest."

The Early History of Tin Plate is shrouded in mystery, for in those days secrecy was the only means by which inventors were able to protect themselves and secure any benefit from their inventions. Although it is certain that the art of coating iron with tin was known and practiced before 25 A. D., the tin plate industry is supposed to have originated in Bohemia, some time after the discovery of tin there in 1240. There, the process was a zealously guarded secret for many, many years, but about 1620, the Duke of Saxony secured enough information, through an agent sent into Bohemia disguised as a priest, to enable him to begin the manufacture of tin plate in his own duchy. These countries exported large quantities of their product to England, where it was used for making body armor, shields, and various ornamental and useful vessels and trinkets, and for roofing parts of churches and other public buildings. Now, England produced considerable iron in those days, and in Cornwall and the Scilly Islands were what are now the oldest tin mines in the world. Here, a thousand years before the birth of Christ came ships out of Tyre and Sidon for tin, which they carried back to Phoenicia for use in the manufacture of bronze. So, in 1660 or 1661, Andrew Yarranton set out on a visit to Saxony, where he succeeded in learning some of the secrets of making tin plate. On his return, about 1665, he began to experiment and apply the knowledge he had gained in Saxony, and in 1670 had begun the manufacture of tin plate in England. Owing to many things that tended to hamper its progress, the new art gained little headway as an industry until 1720, when it was established in Wales by Major John Hanbury, who started a works at Pontypool.

Iron Used in Early English Tin Plate: An authentic description of the process employed by Hanbury is not available, but from meager information gained from many sources, we have pictured it about as follows: In those days, the base metal or black sheet was made of wrought iron. As the puddling process was not invented until 1780, and coke was not used in the blast furnace until 1735, this iron was made by treating charcoal pig iron in small furnaces known as refinery hearths, or melting fineries, and knobbling fires. In the first, a shallow rectangular hearth was provided for melting and purifying the pig iron. In operating the furnace, charcoal was charged upon the hearth and the pig iron was placed upon the charcoal, which was then burned by means of blasts of air admitted through tuyeres in the sides of the furnace. The heat thus generated was sufficient to melt the pig iron, which trickled to the bottom of the hearth, where the blast impinged upon it, oxidizing the silicon, manganese, phosphorus, and some of the sulphur, iron and carbon. This metal was then tapped, to separate it from the slag, and transferred in charges of

about 200 lbs. to the knobbling fire. Here, damp charcoal was placed upon the metal and burned by means of an air blast, while the metal itself was constantly agitated with a bar to bring it into contact with the blast of air. The oxidation of the iron by the blast, along with other impurities, soon formed a slag that protected the metal from the charcoal, after which the carbon in the metal itself was soon oxidized, causing the metal to "come to nature." Then the pasty metal would be pressed together into a ball with a bar, removed from the furnace, and hammered into a flat bar.

Early Method of Forming the Base Plate: Pieces of this iron were then heated in a blacksmith's fire or forge, and hammered flat and as thin as possible under a helve, a hammer operated by a water wheel. After reheating and smoothing with a hand hammer, several of these rough sheets were piled together, and the pack thus formed was again heated to redness and hammered down to the required thickness. As the temperature of the pack was kept low and each sheet was coated with a film of oxide, the sheets would not weld together. So, after the finishing, the pack was opened, and the black sheets were trimmed to size with a large hand shear, resembling a tinner's snips.

Early Method of Tinning: These sheets, which, needless to say, were of small dimensions, were next immersed in fermented barley water, where they were allowed to remain until they were clean and free of all oxide. They were then removed from the barley water in lots of 15 to 20, washed in water, and placed at once into a pot of hot grease to drive off the moisture. From the grease pot, they were transferred quickly to a pot of molten tin covered with palm oil in which they remained to soak for 20 minutes or more. Upon being removed from this pot, they were probably brushed, dipped momentarily into another pot of tin, and immersed for a minute or two into another pot of hot grease to permit the excess tin to drain off. After most of the hot grease had been allowed to drain off, the coated sheet was placed in a box of barley meal or bran, to absorb the remainder of the grease, and the process was completed by polishing the sheet with the wool side of a piece of sheep skin.

Improvements Leading to Modern Methods of Tinning: From that time to the present, a period of 200 years, many changes, some epoch-making, some of less importance, have been made in the manner of manufacturing tin plate. All these changes have resulted in both bettering and cheapening the product, and are very interesting, but only the most important ones may be mentioned here.

The first sheet rolling mill was constructed in 1728. The idea of substituting rolls to do the work formerly performed with hammers in forming the black sheets was apparently first conceived by John Payne, though Major Hanbury has also been credited with a part in the innovation.

However, there is honor a-plenty for both, for this event marks the greatest step in advancement that has been made in all the history of tin plate. Not only were the rolled sheets superior to hammered sheets in that they were more pliable, more uniform as to gage, and could be made of much greater rectangular dimensions, but they were also produced at a greatly reduced cost. This innovation put Wales in the lead as a producer of tin plate. At first the mill was driven with a water wheel, but, with the perfecting of the steam engine about 1770, steam power was substituted for water power.

In 1770, also, wrought iron made with coke instead of charcoal was first used. This iron was cheaper but of a poorer grade than that made from charcoal. Consequently, this led to two grades of tin plate, which were designated as cokes and charcoals, terms indicative of the quality of the base metal. As already explained, these terms have lost their original significance and now refer only to the finish.

Oil of vitriol, or sulphuric acid, was substituted for barley water as a pickling agent about 1806.

The box annealing of the black sheet was begun about 1829. Previous to this time black sheets were sometimes annealed on a "fire bed," that is, a bed of glowing coals of charcoal was made in the furnace used for heating during the rolling process, and the sheets were placed on this to anneal.

In 1860, the first tinning machine using rolls to carry the sheet out of the tin bath was invented by Moorewood, and successfully put in operation about 1866.

In 1874 a successful pickling machine was invented. During this year, the first tin plate works in the United States were erected at Demmler, Pa., by the U. S. Iron and Tin Plate Company, and at Wellsville, Ohio, by the American Tin Plate Co. Both failed, as they could not compete with imported tin plate, and, in 1878, these plants were turned to the manufacture of light sheets, much of their product being used in making enamelled ware.

In 1876 the first attempt to roll Bessemer steel into sheets was made at the Demmler works, and by 1880 steel had been generally substituted for iron in the manufacture of tin plate in England. At first, Siemens, or open hearth, steel was substituted for charcoal iron, while Bessemer steel took the place of coke iron, but now even this distinction has been dropped.

Besides these improvements, some other changes of importance, the exact dates of which we have been unable to ascertain, were made. These

changes include the cold rolling of the black sheet, by which the finish is much improved; the use of a flux instead of the grease for drying the sheet previous to tinning; the mixing of lead with tin to produce terne, or dull finish, plate for roofing purposes; the invention of the power driven trimming shear; and various minor improvements in heating furnaces. Suffice it to say that as a result of these improvements, Wales was able to lead the world as a producer of tin plate for more than 175 years. Indeed, in 1890, she was the only large producer of tin plate in the world; in that year her output is said to have exceeded 13,000,000 base boxes, about 70 per cent. of which was exported to this country. In that year, the McKinley tariff bill was enacted, and tin plate was given a protective tariff of 2.2 cents per pound. As soon as this bill became operative in 1891, the manufacture of tin plate was resumed at the Demmler works, but it was not long until other works began to spring up at various points in Pennsylvania, Ohio, and some other states. In short, as a result of this governmental protection, the industry has grown by leaps and bounds in this country, so that our annual production of tin plate now exceeds 30,000,000 base boxes. This rapid growth was largely due to the invention of automatic can-making machinery, which began to be put into operation soon after 1890. About two-thirds of our total output of tin plate now goes into the manufacture of tin cans and containers.

SECTION II.

MODERN METHODS OF MANUFACTURING TIN PLATE IN THE UNITED STATES—ROLLING THE BLACK PLATE.

Steps in the Manufacture of Tin Plate: As the reader will now surmise, there are many steps in the manufacture of a tin plate. Some idea as to the great number of such steps and the great amount of work done in producing the finished plate can best be formed from an outline such as the following:

Table 101. Processes and Operations to Produce Tin Plate.

- **Preparation of the tin bar (Steel Dept.)**
  - Manufacture of pig iron from ore with limestone and coke.
  - Purification of pig iron
    - Bessemer process.
    - Open Hearth process (acid. / basic.)
    - Duplex processes (Bess.-O.H.)
  - Casting Steel into Ingots.
  - Rolling Ingots into Blooms.
  - Rolling Blooms into Tin Bar.
- **Rolling the Black Plate (Hot Mill Dept.)**
  - Shearing the tin bar into proper lengths.
  - Heating the bars.
  - Rolling the pairs.
  - Matching the pairs.
  - Parting and doubling the pairs.
  - Reheating pairs.
  - Rolling sheet pack.
  - Doubling and reheating the sheet pack.
  - Finishing, rolling, the pack.
  - Shearing the pack.
  - Opening the pack.
- **Preparation of the Black Plate for Tinning (Pickling, Cold Rolling and Annealing Dept.)**
  - Black Pickling.
  - Black Annealing.
  - Cold Rolling.
  - White Annealing.
  - White Pickling.
- **Tinning the Plates (Tin House Dept.)**
  - Drying the Plates.
  - Coating the Plates.
  - Cleaning the Plates.
  - Polishing the Plates.
- **Inspecting and Boxing the Plates (Inspection and Boxing Dept.)**
  - Assorting the plates into
    - Primes.
    - Menders.
    - Seconds.
    - Waste Sheets.
  - Reckoning
    - Counting.
    - Weighing.
  - Boxing.

The Tin Bar: From this outline, it will be seen that the rolling of the black plate is similar to the rolling of light sheets. The tin bar is received from the steel department or works in lengths of approximately 30 feet. This bar is 8 inches in width and varies in thickness, in steps of a tenth or two-tenths of a pound, from 6 to 16½ pounds per linear foot, in order that sheets of different gages and lengths may be rolled from it. It is made of soft steel, known as tin plate quality, by any of the standard steel-making processes, though the greater portion is produced by the open hearth process. This bar should be free from such defects as pipes, blisters, seams, slivers, scabs, brick spots, and heavy scale, and should be as near to the weight specified as possible.

Size of the Bars: The first step in filling an order at the tin mills is to calculate the size of bar to use to produce the plate required. In making this calculation, due consideration must be given to the gage of the plate, its rectilinear dimensions, and the way in which it is to be rolled. Formerly, tin plate was made in standard sizes. For a long time the standard was 14″ x 20″, and later it was 20″ x 28″. Such standards are of great advantage to the mills, but, in order to avoid waste, the mills have sacrificed this advantage, so that their customers may order their tin plate in the size that will work up to best advantage and with as little scrap loss as possible. That there are certain limits as to the maximum sizes that can be made will be evident from the descriptions to follow. But even the largest tin plates are too small to be handled economically on the hot mills in single lengths, so they must be rolled in multiples. In many of the uses to which tin plate is put, the direction of the "grain," or fiber structure, of the steel in the plate is important and must be considered in making up the multiples. Hence, in one case it may be necessary to roll 20 x 28-inch plates, for example, in multiples of two, or 20 x 56 inches, while in another case, in multiples of three, or 28 x 60 inches.

Shearing the Bars: When the plan of rolling has been decided upon and the necessary calculations have been made, a bar meeting all the specifications as to weight and quality is selected and sheared into the lengths required by the plate, plus a certain allowance for scrap. The shears used for this purpose are of many types, representing different stages in the evolution and growth of the industry in this country. In modern plants, a vertical shear similar to a plate shear is employed. This shear is equipped with a live-roll approach table, an automatic stop, and a receiving platform. The bars are placed upon the approach table in about 5-ton lots with a crane, whence 4 to 6 at a time are distributed upon the rollers with a hook in the hands of the sheartender. The shearman then operates the rolls in the table, the stop, the receiving table, and the shear clutch without moving from his position at the end of the shear. In this way the half dozen 30-foot bars are sheared into the lengths desired very quickly. As they are sheared off, the bars drop into neat piles on

a cradle resting upon the receiving table, which can be moved out to one side when the cradle is full, thus giving the crane an opportunity to lift the cradle to a truck or other conveyance that will carry the bars to the hot mills. The exact manner of transporting the bars to the hot mill depends upon the size and layout of the mill. If the shear is at one end of the hot mill building, for example, the crane itself would deliver the bars, which are hereafter to be called pairs.

The Hot Mill Equipment: In ordinary practice, the equipment of a hot mill unit is comprised of one stand of rolls, a pair furnace, a sheet furnace, a doubling machine and shear, and a squaring shear. The arrangement of this equipment in the plant is very much the same as for sheet mills. The number of roll stands in a train range from 2 to 12, though 6, 8 or 10 are the most economical to operate. Likewise, all types of drive are encountered. In one of our most modern plants, the 48 stands of rolls, all set up in one straight line, are grouped in double trains of 8 stands each, 4 stands on each side of the drive. Each train is driven from the middle with an electric motor, connected through gears so as to reduce the speed from 100 r. p. m. to about 30 r. p. m. Only the bottom roll on all tin mills is driven; if a roughing stand is used, its top roll is a jump roll. One roll on the finishing stand of any sheet mill must be friction driven, for the driving of both rolls causes the sheets in a pack to weld together. Apparently, the drag of the friction driven roll on the pack creates a slight slipping of the sheets that prevents their welding under normal practice.

The Rolls are made of chilled iron and are ordinarily 26 or 28 inches in diameter and from 30 to 44 inches in length. The diameters of the necks are approximately .8 that of the barrel, and each roll carries a 4-pod wobbler on each end. The depth of chill on the new rolls varies from ¾ to ⅞ inch, and one roll in each mill is turned concave, so that when they have been warmed up to a proper working temperature, the longitudinal surface lines on the two rolls will be as nearly parallel as possible. The temperature of tin mill rolls is maintained slightly higher than sheet mill rolls, usually at about 750° F. The warming up of the rolls requires at least one full turn, unless heaters are used, and, though narrow sheets are rolled during the first turn, it is obvious that these sheets cannot be as uniform in gage as those rolled later. The rolls are used until the hollowness due to wear begins to affect the gage of the sheet noticeably, when they are taken out to be redressed. Usually, a new or redressed set of rolls is required semi-weekly. They are, of course, polished as often as necessary. The mill screws are adjusted by means of a spanner bar and levers. The housings are massive, weighing from 30,000 to 32,000 lbs. each. The spindles connecting the different stands of rolls in a train are from 16 to 20 feet long, in order that both pair and sheet furnaces may be set side by side and be accessible from the standing, or doubling floor. The usual foreplate is inserted between the housings on the roller's, or

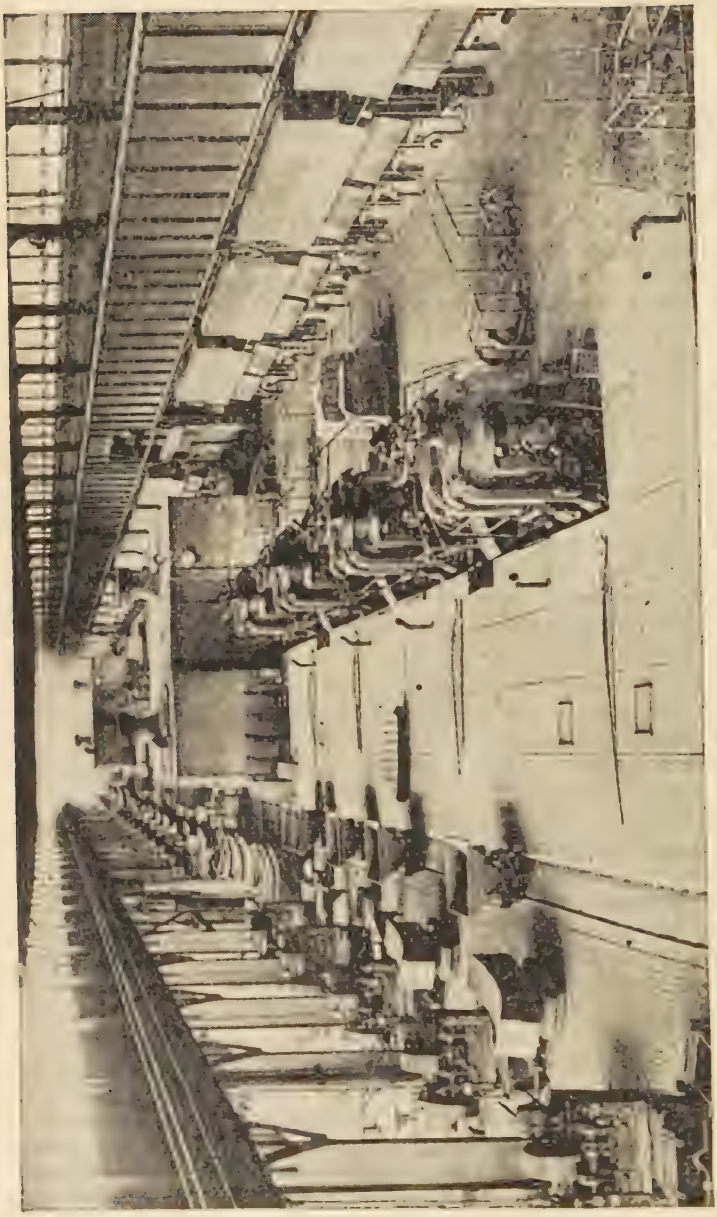


Fig. 267. Hot Mills of a Modern Tin Plate Plant.

entering side of the mill, but the catchers rigging consists only of a couple of guides against the lower roll, and a billy for returning the sheet or bar over the top roll.

The Pair and Sheet Furnaces: As in the case of sheet mills, there are about four different types of pair furnaces in use for heating the pairs. These include the old square, simple types in which the heating chamber is separated from the combustion chamber usually by a bridge wall; the tandem combination pair and sheet furnace; the Allis continuous pair furnace; and a recuperative gas-fired pair furnace. Some of the most recent installations, however, would appear to presage a return to the oldest and simplest type, with certain improvements, of course. The advantage in this type, is that the pair furnace, being of the same size as the sheet furnace, can be built en bloc with the sheet furnace, and all the furnaces of the plant can be arranged in one straight line with all firing chambers in the rear and all doors opening upon the doubling floor, or standing. This layout makes an ideal one for firing with mechanical stokers or powdered coal, and, as coal is the most reliable and widely available fuel, it exerts an influence on furnace design. Other fuels are being used, but due to these facts, and that a high temperature is not required, but a slow, even heating in a reducing atmosphere is desirable, coal fed by mechanical stokers has proved the most satisfactory. The best stokers for the purpose are of the underfeed type. Since with this type of furnace, there is little difference in construction between the pair furnace and the sheet furnace, this plan makes it possible to change a pair furnace into a sheet furnace, and a sheet furnace into a pair furnace. The heating of the tin bars is conducted with the same precautions as are observed in heating sheet bars. They are charged in heats of from 18 to 30 pairs, depending upon the gage and the length of the finished sheet pack. Short sheets take larger heats, because the rolling time is shorter and relatively more time for heating is required.

Doubling Machines and Shears: The older machines, still generally used, for doubling and shearing are known as doubling shears. This machine consists of a lever, or alligator, shear and a pair of doubling irons set at right angles to the shear. The lower blade of the shear and the lower doubling iron are attached to two adjacent edges of a heavy square table which stands about 28 inches high. The upper doubling iron is securely attached to the upper shear blade just in front of the fulcrum, so that the doubling irons open and close with each double stroke of the shear. With this device, the pack must first be doubled by hand and the bend, or curl, flattened somewhat with the foot, when the pack is laid upon the shear table and the curl pushed between the doubling irons on an upstroke of the shears, to be pressed flat on the down stroke. Then, by turning the pack 90°, the horns and the old curl may be sheared off on another stroke of the shears. Special devices, by means of which these operations may be performed mechanically, are now used in some mills.

Operation of the Mill: In starting up the mill the same precautions in warming up the rolls must be observed as for sheet mills. As to rolling, the details of the manipulations must be adapted to the gage of the sheet or plate. Ordinarily, the practice is to finish all sheets heavier than 20 gage in packs of 2, single iron, and all other gages as follows:

20 to 27 gage,	4	sheets	in a	pack,	double iron.
28 to 29 "	6	"	"	"	"
30 to 34 "	8	"	"	"	double-double iron.
35 and lighter,	16	"	"	"	taggers, made by combining two packs of eight sheets each.

More than two-thirds of the tin plate made requires black plate between 30 and 34 gage. Therefore, the rolling of an eight-sheet pack is selected to illustrate the manipulations necessary in order to produce the black plate.

Fig. 268. Breaking Down the Bars—Roller's Side.

Roughing: With the pairs heated to the proper temperature, they are removed in twos from the pair furnace with a pair of tongs and laid upon the fore plate of the mill. Here, any scale or dirt that may be adhering to the bars, a thing that should seldom happen, is removed with a stiff steel brush, when the rougher immediately grasps one of the bars with his tongs and passes it laterally through the rolls. Then the catcher grasps it and returns it over the top roll to the rougher, who has, in the meantime, fed the second bar through the rolls. The screw is tightened, and the bars are given a second pass as before. These operations are repeated until each bar has received about five passes, when the pairs

are generally matched and reheated again. The matched and reheated pairs are next rolled to a definite length, when the sheets are pulled apart, rematched, and doubled before reheating for the next rolling. When done by hand, this doubling requires skill, but if a doubling machine is used, it may be done by any one able to separate the sheets in the pack. The half-formed sheets are now delivered to the sheet furnace, or the "fours" furnace, to be reheated.

Fig. 269. Roughing—Rolling the Matched Pairs—Catcher's Side.

Rolling the Pack: The sheets now come under the care of the sheet heater, who grasps the open end of the pack with long handled tongs and lifts and pushes it through the door of the furnace, when, turning it on edge, he leans it against one of the side walls of the furnace. Here it remains until almost hot enough to roll, when it is turned down flat upon the bottom of the furnace directly in front of the door. With their temperature properly restored, the packs, now known as fours, are returned to the mill and given two or three passes, which should elongate them to the length of the sheet desired. In feeding the pack to the rolls the curled end is always foremost. Being very thin, the fours cool rapidly,

so that two passes usually represent all the reduction possible here. They are, therefore, opened and doubled as before, but after doubling, in this case, the open end of each pack is sheared off to remove the curl left from the fours and square up the end of the pack. These packs of eight sheets are now reheated in the same manner as the fours, when they are given sufficient passes through the rolls to draw them out to the required length, which is determined by the roller with a measuring rod, or gage pole. After the last pass, the catcher draws the pack to one side and places it with others to form a neat pile, where it is allowed to remain until it has cooled to atmospheric temperature, and is ready to be sheared.

Fig. 270. The Sheet Roller Finishing the Pack.

Efficiency of the Method: From this description, it will be noticed that the hot mill remains, both in construction and operation, about as it was in the beginning. Though many attempts have been made to improve it or employ another type of mill, none have succeeded, because no other method yet devised will give a black plate as uniform in gage or as near the weight called for.

Hot Mill Defects: Many defects of the black plate may be produced in the hot mills, and constant care on the part of all the workmen is required to avoid them. These defects include rough spots due to dirty bars, to dirt or scale collected from or formed in the heating furnace, to the use of worn out rolls, or to rough spots on the rolls. If the roller is not careful in gaging the pack, short sheets or plates with round corners may result. If, during the rolling, any of the hot neck grease is dropped or splattered upon the pack, it not only spoils several sheets in the pack, but may mark the roll as well. If the temperature is too high, or if the roller uses too much pressure in rolling, "stickers" may be produced, which will give rise to sticker holes and patches. Two other common defects are those known as bucklers and pinchers. Bucklers are sheets in which the metal has flowed over itself in rolling, forming a lap that extends across the sheet. They may be caused by cold spots in the pack or from certain parts of the pack slipping or sticking. Pinchers are caused by hollow rolls or any other condition that causes the metal to overlap. This defect usually appears as a lap or seam located near the middle axis of the sheet and extends parallel to the direction of rolling.

The Squaring Shears are of the vertical guillotine type, and are operated with a small electric motor. Formerly two men, or a man and a boy, called a hand-over, were required to operate these shears, but they are now equipped with automatic hand-overs and are operated by one man. These devices are attached to the backs of the shears to receive the plates as they are cut by the shear blades. In front, each shear is provided with a squaring table, which carries two straight edges set at right angles to each other. One of these, called the back guide, extends parallel to the shear blades and is made adjustable so as to be moved nearer to or farther away from the shear blades. These shears, one for each mill, are arranged in a single row along the cooling floor, so that the pile of sheets can be delivered to them with a crane. When this is done, the shearman grasps each cold pack at the curl, and, pushing the open end through between the shear blades, steps on the clutch pedal and cuts off a section long enough to give the plate required with about a half inch over. With the stroke of the shear blades, the longer end of the pack drops upon the hand-over out of the way, while the shearman turns his portion around, and, with the sheared edge pressed against the back guard, shears off the curl. Then, after shearing off the two remaining edges and thus squaring up this portion, he presses a pedal which causes the hand-over to rise and, by a kind of shuffling motion, projects the second half of the pack through between the shear blades toward him. This second half is then squared up as was the first. By this method the greater portion of the scrap comes off the open end of the pack, which is, therefore, known as the scrap end.

Opening the Pack: The squared packs are now opened, as in the case of sheets, but in this case the work is performed with the hands, a

Fig. 271. Shearing and Opening the Packs.

small tool being worn in the palm of one hand with which to bend over the corners and start the opening. Stickers, of course, must be sworded open. The plates are hastily inspected here, or sorted, by the opener, and all that contain visible defects are discarded. During the shearing and opening operations, and, indeed, throughout all the succeeding processes, the plates must be carefully protected from dirt and grease. The perfect plates are now loaded on buggies and taken to the pickling department, the buggies sometimes being pulled along by an electric truck, operated from storage batteries.

SECTION III.

PREPARATION OF THE BLACK PLATE FOR TINNING.

Black Pickling is the first step in the preparation of the black plate for tinning, and has for a chief object the removal of all the scale from the surface of the plate. All pickling is now done by machines, of which there are two different makes, known as the Gray and the Mesta machine. Though different in construction, both employ the same principle in pickling, namely, that of plunging the sheets supported on edge in a cradle up and down in the acid. The Mesta machine has already been described in connection with the finishing of sheets. In the case of the Gray machine, the pickling tank and washing tanks are set end to end. Directly above these, at a height of 8 or 10 feet, is a monorail trolley track arranged in an oval horizontal runway, so that the trucks can make a complete circuit, passing over the center line of the tanks. A section of this track over the tanks is separated from the rest of the runway and attached at each end, through two levers, to two long steam or compressed air cylinders. In operating this machine, a cradle, which hangs suspended from the trucks above, is loaded with the plates in the usual way at one end of the oval, after which it is pushed forward until it is directly over the pickling bath and is supported by the section of track attached to the plunger cylinders. Then, by merely turning a throttle, the whole section of track is lowered, immersing the sheets in the acid, where they are plunged up and down until free from scale. Then the track is raised to its highest level, the truck and cradle of plates are moved over the washing tank, and the plunging is resumed. When the plates have been washed, the truck may be pushed forward upon the fixed track to the farther end of the oval, where the plates are removed from the cradle. The concentration of the sulphuric acid used is about 4 per cent.; the temperature of the pickling bath is about the same as for sheets, between 180° and 190° F.; and the time of the pickling is from 8 to 10 minutes. Under these conditions

the pickling loss is about 2 per cent. of the weight of the plates pickled. By adding concentrated acid to the bath, its strength, or concentration, is maintained until the gravity reaches about 30° Baumé, when the addition of the acid is stopped, the excess acid is neutralized and a new bath is prepared.

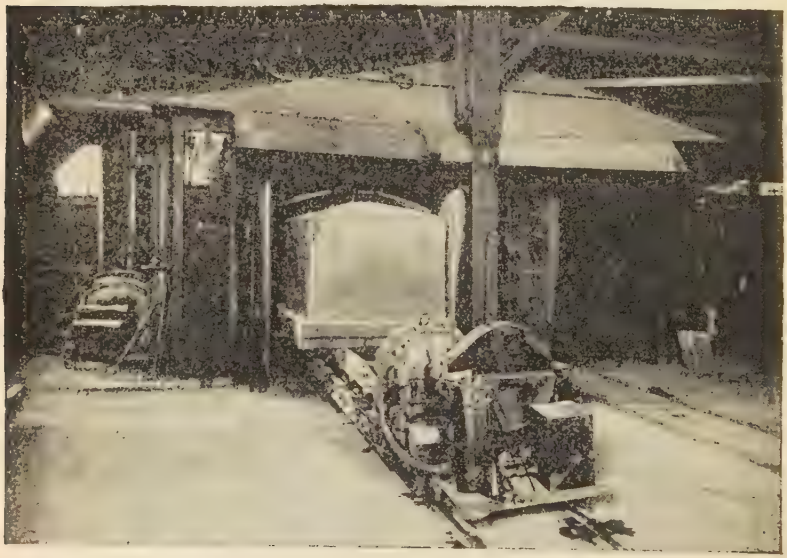


Fig. 272. Annealing Furnace Showing Charging Machine in Operation.

Black Annealing Equipment: As the plates are removed from the pickling rack, they are carefully inspected individually for black spots, where the scale has not been removed, and also for other defects. The plates that pass this inspection are then stacked, in two piles and side by side, to a height of about 4 feet, upon an annealing stand or bottom, when they are covered with a lid, and sealed in with sand about the base of the cover. The bottom, or stand, is made of cast steel, but the lids are now generally made of ¾-inch steel plates welded together. In some cases the plates are reinforced with angles, or the plates themselves are corrugated, to prevent or overcome the tendency to warping; but as these improved forms are somewhat more expensive and will warp in time, anyway, the plain welded steel cover is generally preferred. The boxes thus charged are then carried by overhead crane to the annealing furnaces and placed upon an electric charging machine. This machine is a very ingenious device. It consists of a truck, mounted upon wheels so as to be drawn

in and out of the furnace easily, and a top carriage, mounted upon wedge-shaped bearings that ride a similar number of small wheels attached to the upper frame of the truck. By means of a mechanically actuated screw attached to the rear end of the carriage and working through a nut anchored to the frame of the truck, the carriage may be moved back, raising it to a higher level, or moved forward, when it descends to a lower level. All these parts are actuated by means of an electric motor mounted upon the rear of the carriage. With this machine, two or more of the charged boxes are moved into the furnace and lowered upon fire brick supporting walls, when the carriage, continuing its descent to the lower level, is withdrawn without the boxes. The annealing furnaces may be of a type similar to sheet annealing furnaces, fired at one end and with a capacity of but three to four boxes, or of the camel-back type, which is fired at both ends and has a capacity of from 8 to 16 boxes. The latter are called camel backs because the roof slopes upward from each end to a comb in the center.

The Black Annealing Operation is of the utmost importance, not only to the tin plate manufacturer but to the consumer as well, and requires great care to secure satisfactory results. The black plate is hard, stiff, and somewhat brittle; presents a decidedly striated grain structure due to the rolling in the hot mills; holds considerable hydrogen absorbed in pickling; and carries a film of water on its surface that may contain some

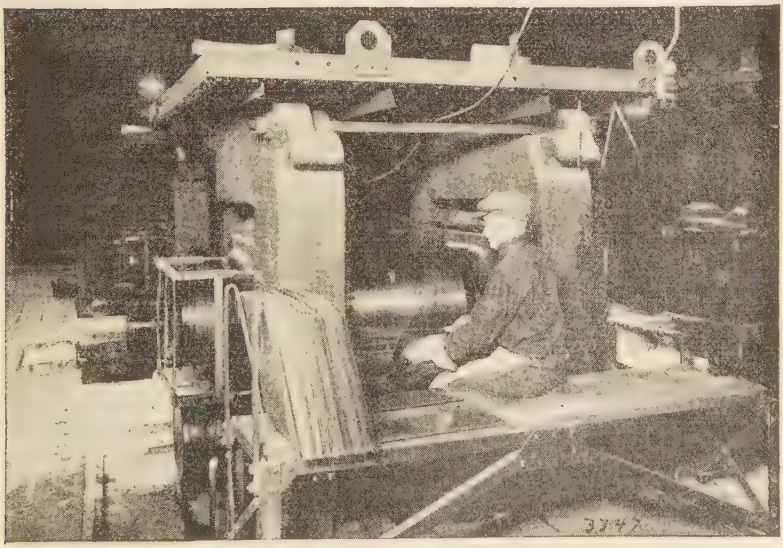


Fig. 273. Cold Rolling the Black Plate.

iron salts in solution. To remove the rolling strains and stresses, drive off the absorbed gases, and clear up the surface of the plate are the objects of this annealing operation. To accomplish these results a comparatively high annealing temperature is necessary, yet if the plates are heated to too high a temperature they will stick together, forming an almost solid mass that cannot be parted. A temperature of about 1400° F. (760° C) is generally aimed at. This temperature may cause the sheets in the pile to stick together, but by hammering them, not too heavily, with a round-headed maul, they may be loosened enough to be parted, though not without much labor and expense. If the hammer blows make too deep indentations in the plates, cold rolling may not remove them, and the plates will be marred. The charged boxes must be heated slowly, and carefully soaked, so that they usually remain in the furnace 16 to 18 hours, when they are withdrawn from the furnace and allowed to cool, with the covers on, to atmospheric temperature. This cooling requires from 40 to 48 hours. The covers are then removed and the loaded bottoms taken to the cold rolls, where the piles are loosened, and the plates are parted as described above.

The Cold Rolls: The pickling and annealing operations through which the black plate has just passed leaves it with an etch-roughened and porous surface, which would not only absorb a large amount of tin in the tinning process, but would make it almost impossible to obtain the highly polished, mirror-like surface characteristic of high grade tin plate. Furthermore, the plate contains many deformations from the previous handling. To overcome this drawback and flatten the plates, each one singly is given three passes through cold rolls, which produce a dense, polished surface on both sides of the plate. These cold rolls are similar in construction to the cold rolls used in the sheet mills, but they are set up in three parallel tandem trains of from 2 to 4 stands each. These trains are known as the roughing, middle or intermediate, and finishing trains, and are all driven from one end with one engine, or motor, either through gears or by means of ropes and pulleys. The intermediate train is separated from the roughing and finishing trains by spaces of about 8 feet, which are bridged with conveyor belts to carry the plates from the roughing to the intermediate and from the intermediate to the finishing stand. Since the rolls are thus arranged to operate on the continuous plan, each train is driven at a slightly faster rate than the preceding one. The usual speeds range from 38 to 42 r. p. m. for the roughing rolls, from 40 to 44 r. p. m. for the intermediates and from 42 to 44 r. p. m. for the finishing. The exact speed varies according to the diameter of the rolls, which is usually 24 or 26 inches. The length of the bodies or barrels correspond to those of the hot mills. As the rolls are worked practically cold, they are turned perfectly straight on the bodies.

Operation of the Cold Rolls: Since the cold rolling bears a most important relation to the final finish of the tin plate, the surfaces of the

rolls must at all times be kept perfectly smooth and clean. They must, therefore, be frequently polished with emery while in use, and if the surface becomes deeply marked, it is necessary to remove them from the housings and redress them in a lathe. Great skill is required to adjust the rolls properly, after returning them to their housings, for, since the plates are not subjected to any succeeding levelling operation, the cold rolling must not only fulfill all the usual functions of cold rolls but must also leave the plate properly flattened. The neck must be carefully lubricated, for which purpose grease of cold neck quality, somewhat lighter than hot neck grease, is used. At first, the necks heat up faster than the bodies of the rolls, causing them to expand near the ends and to become a little hollow. Wide plates are likely to be crimped on the edges, and it is desirable, when possible, to roll the narrower plates for the first three hours, at the end of which time the mill will have become thoroughly warmed up and the rolls perfectly parallel again. The plates may now be fed into the first, or roughing, stand, one after the other and as rapidly as possible, when they will be carried through the intermediate and finishing stands by the conveyors. With this arrangement, one stand of cold rolls working 8 hours can easily roll the output of two single hot mills working 24 hours per day.

White Annealing: The plates are slightly hardened by the cold rolling, and to relieve the cold rolling stresses and soften the plate it must again be annealed. Therefore, the plates are again assembled and piled, or stacked, on annealing bottoms, which are then covered, sanded, and charged into annealing furnaces as in the case of black annealing. But the plates, now perfectly flat and having a smooth, polished surface, cannot be heated to as high a temperature as formerly, on account of the danger of sticking them together again, which sticking would now ruin them entirely. Fortunately, such a high temperature is not now necessary, as heating to 550° C. (1022° F.) is sufficient to remove the cold rolling strains and restore the softness of the plates. From 10 to 12 hours time is required to bring them to this temperature, when they are withdrawn from the furnaces and allowed to cool in the annealing box to atmospheric temperatures before the covers may be removed.

Tin Mill Black Plate: It should now be pointed out that not all the output of the tin mills is coated. By varying the order of these processes, arresting the plate at different points as it passes through these preliminary processes, and, in some cases, supplementing these with other processes, it may be adapted to various uses, such as in the manufacture of toys, tacks, lye cans, trunks, stove pipe, milk cans, enameled ware, tea trays, buttons, signs, ferrotypes, and many other things too numerous to mention here. The supplementary processes are bluing and polishing. Polishing is accomplished by passing the plate, at proper temperature, through the cold rolls, while bluing is effected by treating the plate, which

has been heated and cooled to certain temperatures out of contact with the air, with either air or steam. All these products are classed as tin mill black plate.

White Pickling: During these annealing and cold rolling operations, a light film of oxide, varying from a dark blue about the edges to a slight yellowish discoloration nearer the centers, forms on the surfaces of the plates, and it now becomes necessary to remove this film of oxide before the plates can be tinned. Therefore, they are taken to the white pickling department, where they are pickled in about the same manner as in the case of black pickling. However, the acid for this operation is much weaker, a 2-per cent. solution being used; the pickling bath is kept at a slightly lower temperature; and the time of pickling is but from 3 to 5 minutes, the object being to remove the oxide without etching the surface of the plate any more than is necessary. Over-pickling here will cause the plate to take up larger amounts of tin and make it more difficult to secure a polished, lustrous surface. After this operation, the plates are washed for a similar period in clean cold water, then carefully inspected and placed in storage boshes filled with water until such time as they may be taken to the tinning department to be coated. The storage boshes are rectangular tanks, usually about 2 ft. wide, 5 ft. long, and 4 ft. deep, and are now generally made of steel plates welded together. They are mounted on four wheels so as to be readily trucked, or pushed by hand, over tracks laid in the floor of the shop. To prevent surface oxidation of the white plate, a little hydrochloric acid is added to the water in these boshes. With the water treated in this way the white plates may lie immersed in it for several days, or weeks, without injury. Indeed, a long period of immersion is beneficial to the plate, for it permits the total escape of the absorbed hydrogen, which is very detrimental to the tin coat if allowed to remain in the plate. In this connection it should be emphasized that clean, well made steel does not absorb hydrogen to anything like the extent to which dirty or highly oxidized steel does.

SECTION IV.

TINNING COKE AND CHARCOAL PLATE.

The Tinning Department is composed of a number of tinning stacks, as they are commonly called, arranged usually along each side of a long rectangular building. The number of these stacks depends upon the number of hot mills serving them. Ordinarily, one tinning stack is required to tin the output of one hot mill, though recent improvements in tinning machines give promise of doubling this output. The equipment of these stacks consists of a tinning pot for holding the molten tin, a furnace for heating the pot, a tinning machine for carrying the plate through the tin, a cleaning and polishing machine and a cooling table for receiving

the plate as it comes from the pot and delivering it to the cleaning machine. The pot and its setting, the furnace, and the machine comprise the tinning set. Tinning sets are of various types, and depend upon the method of tinning and the kind of machine used, for since the machine must stand in the pot, both the pot and its setting must conform to the machine in size and shape. Most of these sets are comparatively simple in construction, while others represent a more or less complicated assembly of machinery. One of the most recent sets to be brought out is of the latter character. It is an English invention and is known, from its inventor, as the Thomas tinning machine. This set is designed to white-pickle, wash, tin, clean and polish the plates all in one continuous operation and is entirely automatic in its action.

Tinning Machines: In this country, for the tinning of coke plates and the lighter gages of charcoal plate, the tinning machines are of two general types, which may be designated as the single and the double machines. The first type, in its simplest form, is represented by the four-roll Thomas and White machine. These rolls, held in place by substantial housings, are arranged in two pairs, so that the two rolls in each pair lie in the same horizontal plane, and the nips of the rolls in the two pairs lie in the same vertical plane. At one end, the rolls of each pair are geared together, while at the opposite end one roll in each pair carries a larger gear that meshes with an idler mounted between the two pairs. By connecting the gear on the top roll with a small electric motor, the rolls are thus revolved in the proper direction to draw the plates upward when inserted between the rolls of the bottom pair. The rolls are approximately 3½ inches in diameter, but vary in length from 36 inches to 86 inches in the barrel, or body, according to the size of the machine. They are made of high carbon steel (carbon 1.10 to 1.25%) and must be accurately surfaced by machining and grinding. The double type of machine is but another modification of this machine. By increasing the width of the housings, two sets of 4 rolls each are inserted, side by side, making a two-high eight-roll machine with about double the tinning capacity of the single machines. This double machine is commonly spoken of as the Duplex pot.

The Tinning Pots used in connection with these machines, while varying in size to suit the machine, are practically all alike as to their general features of construction. They are each cast, in one piece, of close grained, high grade pig iron, but each consists essentially of two long narrow chambers separated by a partition that extends almost to the bottom, and by an elevation in the bottom that rises to within 3 or 4 inches of the bottom edge of the partition. The slit, or opening, thus left in the partition, permits of a continuous bath of molten tin in the bottom of the pot and provides a passage-way through which the plate may be passed from one chamber to the other. The first, or entering, chamber is rather shallow, being seldom more than 2 ft. in depth, but

Fig. 274. Tinning the Black Plate—Showing the Tinning Machinery in Operation.

the other, the exit or finishing chamber, is about twice as deep and projects above the first. The outer sides of both the entering and finishing chambers slope inward from the vertical somewhat, the first more than the second.

The Setting for the Pot: This pot is mounted on a setting of brickwork, one side, the front, of which contains the fire box, or grate, for heating the tin. The pot is set so that the fore-bottom of the first, or entering, chamber projects about 9 inches into the combustion chamber. In the case of larger pots, flues are provided for by-passing some of the hot gases from the combustion chamber around the outer walls of the pot, thus making it possible to control the temperature of the finishing chamber; but in the case of smaller pots the products of combustion pass directly from the fire box to the stack, which is located in the outer wall of the tin house some 3 or 4 feet off to the right side, or end, of the tinning pot. At a height of 20 feet or more, this flue from the combustion chamber may merge into a larger flue which leads down to the top of the tin pot hood. This hood covers the entire area occupied by the pot, and forms the covering or top of a room, or stall, by which the tin pot is housed on three sides. All fumes from the pot, therefore, pass up this stack. Finally, it should be noted that, for convenience in operating, the pot is set on a level that will bring the top of the entering chamber to a height of about 30 inches above the floor of the shop. The setting and fire box, therefore, are located in a cellar, which is entered by means of a trap-door in the shop floor.

Assembly of the Tinning Pot: Besides these essential parts, several auxiliary pieces of apparatus are necessary to the efficient operation of the pot. Each of these apparatus may vary in form to a considerable extent, so no detail description of them can be given here. A description of the pot as it is assembled ready for operating will suffice to show the relation of all these different parts. To begin with, the pot is filled with molten tin to within about 3 inches of the top of the lower or entering chamber, which height also brings the surface of the tin some 6 inches above the lower edge of the upper partition, thus entirely closing all connection, except through the tin, between the first and second chambers. For this purpose from 5000 to 10000 pounds of pure tin are required, depending upon the size of the pot. The upper part of the second and deeper chamber is now almost filled with pure palm oil, a product that must be imported from Africa. In this palm oil, lies, immersed, the tinning machine, which hangs suspended from the top of the chamber, the housings forming a bridge across each end of the chamber. These housings are securely fixed in position by means of proper lugs and set screws. The level of the tin, the depth of the palm oil, and the height of the machine are all adjusted so that the lower pair of rolls lies 2 or 3 inches above the tin level and the upper or exit rolls at the top of the oil bath and partially exposed to view, so that they may be easily inspected and kept at all times in good

condition for finishing the coating on the plate. About 18 inches above these rolls, is a frame, bearing guides and rolls, which function as lifting rolls to raise the plate out of the finishing rolls and drop it upon an incline, down which it may slide to the conveyor. Going now to the entering end of the pot, a long narrow flux box, of the same length as the bodies of the rolls and open at both top and bottom, is inserted in the upper part of the first, or lower, chamber, so that its lower edges dip into the molten tin for a distance of 3 or 4 inches and its upper edges are elevated an inch or so above the top of the chamber, giving a space some three inches deep for the flux, which is a mixture of zinc and ammonium chlorides. This box is constructed with sloping sides, so that its lower opening is somewhat smaller than the upper, and lies directly before the opening in the partition that separates the first chamber from the second. The space between the flux box and the opening in the partition is guarded both above and below with guides. Similarly, guides are provided in the second chamber to control the path of the plate from the opening in the partition to the nip of the bottom rolls of the tinning machine, but these guides are in the form of plates which act as scruff guards to prevent the scruff from passing back under the upper partition into the first chamber and from being drawn in against the plate as it is entering the lower rolls. The scruff is a mixture of tin oxide and other foreign substances, which float on the surface of the molten tin.

Operation of the Pot: When all these apparatus have been assembled and adjusted as described above, and the baths of flux, tin, and oil have been made up to their proper levels and heated to their proper temperatures, the process of tinning may begin. The pickled and soaked white plates are transferred, several at a time, from the water boshes to a small tinner's box or trough, also filled with water, where they lie immersed and convenient to the tinner's hand. The tinner now takes these plates one by one from the box with tongs and passes them, by means of a tinner's fork, through the layer of flux in the flux box and the bath of hotter molten tin in the first chamber, down through the opening in the partition to the nip of the bottom rolls of the tinning machine. This machine then draws the plate upward through the hot palm oil, stripping off the excess tin, distributing the remainder evenly over the surface of the plate, and raising the plate to a position where it can be grasped by the pull-up, or delivery, rolls above, which deliver it upon the inclined chute that leads to the conveyor. This description applies to the hand fed pots. In 1920 patents were applied for on a mechanical feeding device to take the place of the tinner. This device, through the increase of speed which it permits, more than doubles the output of the pot and produces a brighter, more uniformly coated plate. No especial skill is required to operate it.

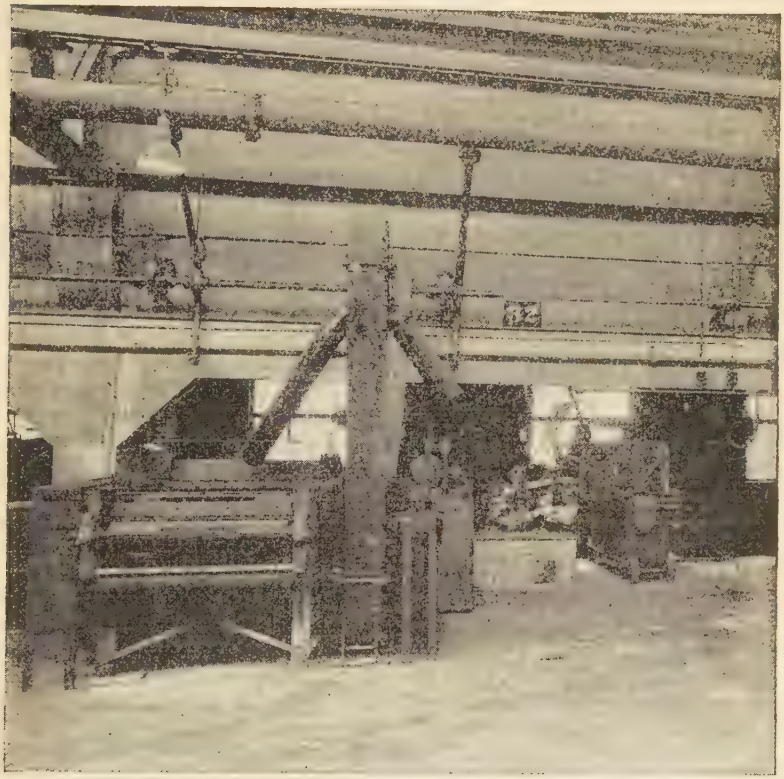


FIG. 275. Modern Tinning Stack with Mechanical Feeder (Right Background) Ready to Operate.

Care of the Pot: Provided the white plate has been properly prepared, the thickness of the coating of tin depends within certain limits upon the temperature of the tin and oil, the speed with which the plate is carried through the bath, and the tightness of adjustment of the rolls in the tinning machine, provided these rolls are kept in good condition. With two of these factors kept constant, the thickness of the coat can be regulated by varying the other, and it is obvious that to secure uniform coating from plate to plate all three must be carefully adjusted, and kept so. The grip of the rolls can be adjusted with screws, and their speed is controlled through the motor that drives them, but the temperature must be controlled by proper firing, and must be watched very carefully. Usually the temperature is determined with two thermometers, one with its bulb immersed half way down in the tin bath of the lower chamber and another

similarly immersed in the oil in the finishing chamber. Pure tin melts at 231.9° C. (449.4° F.), but since it is a function of the tin in the first chamber to heat the plate to the proper temperature for tinning, this tin is kept at a temperature considerably higher than the melting point, usually at about 575°F. One function of the oil is to cool the plate down almost to the fusion point of the tin while still keeping it in a molten condition, so that the rolls may strip off the excess and distribute the remainder as evenly as possible. Therefore, the oil is kept about 100° F. lower in temperature than the tin in the first chamber. Since the oil receives its heat from the molten tin beneath, the temperature of the oil is also an indication of the temperature of the tin in the second chamber, which must be considerably cooler than the tin in the first chamber, else the tinned plate will be lacking in luster and brilliancy. Incidentally, it should be remarked that if the oil is heated to a much higher temperature than this, it gives off rather obnoxious fumes and may take fire or boil over into the first chamber and ignite. Besides this function, the oil, by adhering to the surface of the sheet, protects the hot tin from the air while it is cooling, thus helping to give the finished plate a more lustrous surface. For this reason, the nip of the top rolls must be kept constantly full of fresh, clean palm oil. As to the flux, aside from periodic renewals, it requires little attention. The heat necessary to keep it molten is derived from the tin bath upon which it floats. The most evident function of the flux is to dry the white plate out of contact with the air, but it very probably serves to remove imperceptible films of oxide or rust and sets up a kind of galvanic action that aids the alloying action of the tin and iron, thus causing the coat to adhere more firmly and distribute itself more evenly.

Cleaning and Polishing the Plate: In order to remove the oil that adheres to the surface of the plate as it emerges from the tinning pot, it is next passed through a cleaning and polishing machine. This machine consists of a pair of large housings on which are mounted several pairs of cleaning rolls in tandem. These rolls, which are about 4 inches in diameter, are made by mounting thousands of discs of canton flannel upon a long mandrel. The mandrel is square in section, and the discs are compressed upon it to form a compact cylindrical roll by means of a small hydraulic press, after which they are secured in place by proper rings, washers, and nuts. These rolls are arranged in two groups, or sets, one for cleaning, commonly spoken of as the brusher, and the other for polishing, which are usually designated as the dusting or buffing rolls. The efficient cleaning of the plate requires that a constant stream of a finely ground cleaning mixture capable of absorbing the oil be kept falling upon the cleaning rolls as the plate is passing through them. This mixture, of course, falls down through the spaces between the rolls as the plate passes out. Hence, a hopper is provided under these rolls for collecting and directing this mixture into a small compartment at the bottom of

a small elevator of the bucket type. Here the mixture is raised by the elevator and delivered into a pipe leading down to a point just above the rolls. In this way the cleaning mixture is used over and over until it becomes so saturated with the oil that it is no longer efficient for the purpose.

The Cleaning Mixture may consist of any absorbent material that is soft and fine, so as not to scratch or otherwise mar the surface of the plate. Several different substances fulfill these requirements, such as rye and wheat middlings, bran, sawdust, ground peanut hulls, and finely ground corn cobs. Of these, the rye and wheat middlings in the proportion of about 25 per cent. of the first to 75 per cent. of the second are most satisfactory for cleaning tin plate, for they are not only efficient cleaning agents, but are valuable as a by-product. These substances, containing many food elements and fortified with the fat-giving palm oil with which they are saturated, make an excellent stock food available to our farmers at a comparatively low price. A little powdered lime mixed with the cleaning mixture helps to cut the grease and temporarily gives a more brilliant luster to the plate; but it gives no lasting benefit, adds nothing to the quality of the plate, and renders the cleaning mixture undesirable as a stock food. The same statement applies to lamp black, which has also been used in these mixtures.

Operation of the Cleaning Machine: The plate cannot be cleaned until it has cooled well below the fusion temperature of the tin. Therefore, the plate from the tinning pot is delivered to the cleaner over a conveyor some 18 or 20 feet in length. This conveyor is supported above the floor so as to be on a level to deliver the plate into the nip of the first rolls of the cleaning machine. The standard type consists of a steel frame, at each end of which are mounted two or three sprocket wheels or pulleys, over which endless chains or canvass belts may pass to carry the plate forward. Fastened transversely to these chains, or the belts, are a number of slats, which are preferably angular in shape so as to present a series of blunt knife edges for supporting the plate. This construction lessens the danger of marking the plates and permits them to cool rapidly and uniformly. This conveyor is driven through connection with the cleaning machine. From the conveyor, the plate passes at a corresponding speed through the cleaning and the buffing rolls. These rolls are all connected through gears and endless chains so that they may be driven at different speeds from the same pulley or motor. This varying of the speed of the rolls adds much to their polishing effect, so that the plate is delivered to the receiving bench free from grease and dust and perfectly clean and lustrous.

Tinning of Heavy Charcoal Plates: The process just described is not practicable for manufacturing some grades of charcoal plate. Hence, heavily coated charcoal plates and all charcoal plates weighing 135 pounds

per base box or over are made on Moorewood, or combination pots. As the name indicates, the combination pot is a kind of double pot that permits the use of both machine and hand dipping processes. In carrying out the method, the white plate is first passed through a pot containing a machine very much like the one used for the tinning of coke plates. From the machine, the plates are delivered upon a hob or shelf, from which they are lifted with tongs and dipped by hand into a pot of pure tin kept at a low temperature. They are then dipped into a bath of pure clean palm oil, where, by a system of rolls, the excess tin is stripped off and the remainder evenly distributed. Coming out of this bath, each plate is grasped with a pair of tongs and placed on edge upon a conveyor, which carries them thus to a cleaning and polishing machine similar to that already described.

Assorting: From the receiving bench standing before the buffing rolls, the plates are loaded upon trucks and taken to the assorting room, where they are placed upon well lighted tables for inspection. The inspecting or "assorting" is done by girls and women, because they are much more adept than men at this work. These girls examine each plate minutely on both sides for defects, and classify or assort the plates into four grades, known as **primes, seconds, menders,** and **waste waste**. or **waste plate.** A waste plate is one that contains defects of such an injurious character that it cannot be either corrected by retinning or applied to any use. Such plates are detinned, and the base metal is sent back to the steel plant as scrap to be made into steel again. Needless to remark, in all well managed plants very few waste plates are made. Menders are plates that contain some defect in the coating that can be corrected by putting them through the tinning process again, and accordingly they are returned to the tinning department for that purpose. They also are few in number. Both primes and seconds are shipped out to the customer, and for this reason a fuller discussion of these grades may be interesting.

Primes: Plates graded as primes cannot be considered as perfect plates. While the assorters are well trained and are very expert at their work, they cannot be expected to discover the very minute defects that only an extremely close inspection will reveal, nor those not discernible to the naked eye. The pin holes discussed at the beginning of this description are examples of such defects. Again, while the modern methods of tinning have resulted from hundreds of years of experience, the art has not yet been perfected to the point where the tin can be made to flow evenly and cover uniformly every part of a plate. Thus, the first, or forward, end of the plate to pass through the tinning rolls always carries a slightly lighter coating of tin than the last, or list, end, the list being the small amount of tin that clings to the edge of the plate at this end. Furthermore, the coat not only varies at different points on the same plate, but also fluctuates on different plates. This fluctuation is due to

Fig. 276. Assorting Tin Plate.

the irregularities in the gage and surface condition of the white plates and to variations in the temperature of the tin and oil baths, and, hence, is unavoidable. These small defects and fluctuations in the coat are not peculiar to the more lightly coated coke plates but are found in charcoal grades as well. Indeed, the fluctuations in the coat are even greater in the more heavily coated plates than in the more lightly coated ones.

Seconds: Seconds are plates which will give more or less waste, or scrap, when applied to the purpose for which they are intended. The defect causing the waste may or may not be in the coat. Thus, a plate that has not been properly squared, that has a round corner or a ragged edge, all likely to cause some waste, is classed as a second, though it may have been as well coated as the best prime plate. Again, a plate that contains a small uncoated spot, a blister, or some other defect or series of defects, if these are confined to a small part or area of the plate and easily seen, is classed as a second, because, in working up the plate, these defects may be cut out, leaving the remainder or usable portion of the plate as good as a prime.

Reckoning and Boxing: The assorted plates, primes and seconds, are now counted, collected into packs of 112 plates each, and calculated into base boxes of 31,360 sq. in. each. These operations are called reckoning. Finally, these packs of 112 plates are each check-weighed and placed in a wooden box, properly stamped to show the size, grade, and weight of plate enclosed. High grade charcoal plates are best packed with tissue paper separating the surfaces of the plates, while plates for export are usually hermetically sealed in a tin box, which is then enclosed in the wooden box.

SECTION V.

MANUFACTURE OF TERNE PLATE.

Terne Plate is a sheet steel product obtained by coating the steel sheet with an alloy of lead and tin. It was originally intended only as a roofing material, hence is also known as roofing tin. For this purpose it is supplied by the manufacturer in sheet form, each sheet being 20″ x 28″ in area and either I C (107 lb. per base box, about 30 U. S. S. G.) or I X (135 lb. per base box, about 28 U. S. S. G.) in weight. The lighter material is used for water sheds, and the heavier for spouts, valleys, and gutters. For water sheds, these sheets are first joined end to end to form long strips by means of the locked flat seam. This seam is produced by bending the edges of adjacent sheets over each other, pounding down the bends thus formed until the seam is flat, then soldering along the outside bend. For flat roofs, and roofs of low pitch, the same method is pursued in joining the edges of these strips. Roofing applied in such a manner is known as

flat seam work. The roof is secured in place by means of small cleats, or strips, which are worked into the seams at intervals of about 8 in. and nailed to the sheathing boards. For steep roofs, the strips, made up with flat seams as described above, may be joined with the standing seam. This seam is made by first bending about 1¼ inches along each edge of the strip up at right angles to the surface, then laying the strips side by side and turning down the edges for about ⅜ to ½ inch to form a lock. The soldering of this seam is thus rendered unnecessary. The roofing is secured in place by means of cleats built into the standing seam. Rosin is the only flux that can be used in soldering roofing tin without injury to the surface that may cause subsequent rusting.

Other Uses for Terne Plate: In recent years many other uses for terne plate have been developed, so that perhaps 40 per cent. of all the terne plate made in this country is consumed in the manufacture of articles other than roofing. It is used for deep drawn work with satisfaction, as the coating acts as a lubricant in the drawing operations. It is employed for certain containers, such as automobile gasoline tanks, oil cans, etc., but, on account of the lead-bearing coating, it cannot be used for any kind of food container. For some of these purposes, a sheet larger than the roofing size is desirable, and for such special purposes as these it is produced in sheets as large as 40 x 120 inches in area and from 16 to 30 gage in thickness. These large sheets are known as long ternes, while the 20 x 28-inch size is commonly designated by the manufacturers as short or small ternes. They are also distinguished by the fact that long ternes are made in different base metal finishes, while all short ternes are made to one standard base metal finish.

The Sheet Bar: It is evident that the steel used in the manufacture of terne plate must be very ductile and otherwise of uniformly good quality in order to withstand the severe distortion which nearly all this material must undergo before it is put into service. For this reason many prefer open hearth steel, but with proper care in all departments of manufacture there is no reason why Bessemer steel should not prove satisfactory. So far as the ductility may be affected by chemical composition, there is less difference between the two kinds of steel then some may suppose. The carbon and the manganese content of both is about the same; if there is any difference, the carbon is a point or two higher in the open hearth than in the Bessemer. The sulphur content, which has no influence upon the cold-working properties of the steel, is a little higher in the Bessemer than in the open hearth steel, being between .040 per cent. and .050 per cent. in the latter and about .060 per cent. in the former. Phosphorus, which has the same effect as carbon, point for point, in increasing the hardness and brittleness of steel, ordinarily makes the greatest difference between open hearth and Bessemer steel, but this difference is diminished somewhat in the case of tin bar by the fact that it is necessary to maintain

this element at about .060 per cent. in open hearth steel in order to prevent the sheets from sticking in the pack. The phosphorus content of open hearth tin bar cannot be under .04 per cent. and is usually about .06 per cent., whereas in the Bessemer bar it is .1 per cent. or a little less. This difference of 4 to 6 points in hardening elements is decreased to 3 or 5 points by the slightly higher carbon content of the open hearth steel. This difference cannot be overcome by any treatment, but by careful annealing the Bessemer steel can be rendered ductile enough for all purposes except deep drawn work. Any other differences in the two steels are those incident to the methods of manufacture, and with proper care these may be reduced to negligible quantities, so far as the usefulness of the sheet is concerned. Copper, which has been shown to increase markedly the resistance of steel to atmospheric corrosion, may be added to either the open hearth or the Bessemer steel; and while, in the case of roofing, the best protection against corrosion is to be found in proper laying and watchful care to keep it well painted with pure iron oxide and linseed oil, the use of copper in the steel will undoubtedly tend to increase its life.

Preparation of the Black Plate: The black plate for short ternes is prepared in practically the same manner as plate for tinning. The rolling procedure is the same, and the packs are sheared in the same way. However, it is impossible to do exact cutting on the mill shear, owing to the curved form of the pack. Therefore, an allowance of about ¼ inch in all dimensions of the black plate is left for resquaring on all except the cheapest grade of short ternes. The black plate is etched in pickling a little deeper for the terne coating than for tinning. In black annealing, the plate is heated to the highest temperature practicable and carefully soaked and cooled to make it as ductile as possible. As polish and luster is not so important as in the case of coke plate, terne plate stock is usually given but one pass through the cold rolls.

Resquaring: As explained under hot mill operations, the shearing there is performed under conditions that cannot be exact, and if it could be made so, the cold rolling would probably throw a majority of the sheets out of square, slightly at least. Hence, as the manner of laying tin roof, as well as the methods of manufacturing many other articles from terne plate, require a perfectly square sheet for good work, all short terne plate, except the cheaper grades, must be resquared. This work is performed in two steps, and two different shears are employed. The first step consists in shearing off the edge of one side to make it parallel to the edge of the side opposite. For this purpose a hand-operated shear is employed. This shear is very simple; it consists of a table, provided with an adjustable straight edge stop, for supporting the plate, and a set of shear blades, the top one of which is operated with a foot pedal. The sheets are carefully inspected by the shearman and all defective ones are put aside. The one edge of the perfect sheets is trimmed off, and the sheets are passed

to the end-cutting shear. This shear also has a table and straight edge, but is provided with two shear knives, one on each side, and is machine or power driven, a small electric motor being generally used. In operating this shear, the sheet is laid on the table with one side edge against the straight edge, and adjusted so that each end lies under its shear blade, when, by pressing a pedal, the shear knives descend, trimming off a little metal from both ends, and automatically throwing the sheet upon a receiving stand or table.

White Annealing and Pickling: After resquaring, the plates are white annealed to as high a temperature as possible without danger of sticking, in order to develop their ductility again. Then, as soon as the plates have passed through the white pickling operations, and have been properly soaked in water boshes, they are in condition to be coated with the terne mixture specified.

Brands of Terne Plate: As the reader doubtless knows already, there are many different brands of terne plate, but he may have been puzzled to know how one may differ from another. While the difference between this brand and that brand may be very slight, the difference between these brands when compared with others may be very great, and while it is not the mission of this paper to explain these differences in brands, nor to quibble over details, it is worth while to point out what the fundamental differences may be. These differences may be classified as follows:

A. Differences pertaining to the base plate, i. e., the uncoated sheet.
   1. Difference in manufacture of steel.
   2. " " composition of steel.
   3. " " weight or gage.
   4. " " treatment.
   5. " " finish (long ternes only).

B. Differences pertaining to the coating.
   1. Differences in composition of the coating.
   2. " " weight or thickness of the coating.
   3. " " method of applying the coating.
   4. " " the finish of the coating.

The differences in the base plate have been discussed in preceding paragraphs, so it remains to explain those differences that may occur in the coating.

The Composition of the Coating varies, in practice, from 12 per cent. tin and 88 per cent. lead to 50 per cent. tin and 50 per cent. lead, according to the purpose the material is to be used for. As a rule, the coating for roofing contains approximately 25 per cent. tin, while for long ternes the tin content may be slightly lower. Lead does not alloy with iron, hence

a certain amount of some other element that does alloy with iron is essential. Steel can be coated with lead, but the coat is largely perforated with pin holes, hence it is a very defective one. It would appear, therefore, that the tin first alloys with the iron, and that this iron-tin alloy then acts as a binder between the base and the lead-tin alloy coat. From this standpoint alone, the more tin in the mixture the better, but a high tin content would unduly increase the cost, and defeat the chief objects sought in terne coating. From a cost standpoint, therefore, the tin content should be kept as low as possible. Long experience has established that the lowest proportion of tin that can be economically and efficiently employed cannot be much under 15 per cent.

Thickness of the Coat: Both lead and tin have low solution tensions and are, therefore, almost incorrodible. But while a terne mixture resists corrosion, both lead and tin are cathodic to iron, hence, according to the electrolytic theory of corrosion, both metals will hasten the corrosion of the base metal if any part of its surface should remain exposed. Since there is a tendency, owing to unavoidable minute irregularities in the surface condition of the base metal or to inherent cohesive properties of the alloy coating, for pin holes to form in the coating, such exposure of the base metal can be avoided by the application of the alloy in such a way and in layers of sufficient thickness to cover up and heal over all these spots. Hence, the coating should be a heavy one to insure long life to the plate. The thickness of the coat is expressed in pounds per box of 112 plates, 20 x 28 inches in size, or just twice the area of the tin plate base box. The weight of coat it is practicable to apply varies from 8 to 40 pounds per box, the range being 8, 12, 15, 20, 25, 30, 32, 35 and 40 pounds. While the lighter coatings are suitable for many purposes, such as drawn work and indoor work, for permanent roofing purposes 20- to 40-pound coatings are best to use, the former for water sheds and the latter for valleys, gutters, etc. Even with these heavy coatings, the coating alone should not be depended upon to give full protection against corrosion, and all exposed work should be kept well coated with good paint.

Methods of Coating: There are three general methods of applying the coat to short or small ternes, known as the palm oil, the flux, and the combination process. These terms refer to the kind of flux used in drying and cleaning the surface of the sheet preparatory to the actual tinning process. There are also different methods of finishing the plates, which treatment is applied immediately after the completion of the coating process. These are known as the oil finish and the dry finish, each of which may be carried out in slightly different ways. While the details of each process forms an interesting study, space will permit but a brief exposition of the more fundamental principles in the few paragraphs to follow.

The Palm Oil Process is the original one for the tinning of sheets, and with a few minor modifications is still used to produce short terne

plate when so ordered. The apparatus, which as a whole is commonly known as a stack, consists of four or five pots for containing the molten lead-tin alloy and the oil or grease, and a furnace or furnaces for heating them. The pots are arranged side by side on top of the furnace, which may be provided with different grates and flues so that the temperature of each pot may be regulated as desired. As the tops of the pots must be kept at a height above the floor of the tin house convenient for working, the furnace is wholly beneath this floor.

Operation of the Palm Oil Pot: Briefly, the operation of the stack is carried out about as follows: The sheets from the white pickle are taken from the boshes as required and placed under water in a tinners box or bosh, whence they may be conveniently removed for tinning. From this box a number of the sheets are placed consecutively in the first pot, which contains palm oil kept at a somewhat lower temperature than the terne pot. Here they are "boiled" for about 20 minutes primarily to evaporate the water from their surfaces. Incidentally, this heat may drive off occluded hydrogen and free the sheet from any acid or other corrosive substances that may be adhering to its surfaces. The perfectly clean and dry sheets covered with the grease are then passed into the next pot, which contains the terne mixture in the molten state and covered with a layer of oil. From this pot they are passed all at once to a second metal pot, where they are allowed to soak in the molten alloy for several minutes. The "batch" of plates are then lifted out of this pot and placed on a table of iron plates, called the hob, between this pot and the next, or third, terne pot. Here they are cleaned, if necessary, then dipped with tongs singly into another pot filled with clean metal of extra fine quality, and immediately transferred to a grease pot containing clean palm oil or palm oil and tallow. The length of time the plates remain in this pot depends upon the weight of coat desired, provided the temperature of the oil is kept constant, which is an essential condition to the proper operation of the pot. It is to be especially noted that if the plates are "sweated" long enough in this oil, practically all of the metal can be stripped off. Hence, neither the method of coating nor the fact that the plate has previously been "redipped" in the metal is a guarantee that the plate carries a heavy coating of terne metal, and consumers of terne plate should see that the weight of coat is stamped on each plate or that the weight of the coat is guaranteed in some other way than by the assurance that it has been redipped. Coming from this pot, the plate may be dipped again in oil, either palm oil or a special mixture, to give an oil finish, but for dry finish this step is omitted. In either case, the sheets are taken from the last pot and placed on edge upon a special conveyor that carries them to the branning machine, being cooled, if desired, by fans or air blast on the way.

The Flux Process has been called the acid process, but this latter appellation is a misnomer. The process involves the use of a flux for final

cleaning and drying of the base plate and of a tinning machine similar in construction and operation to that used in the manufacture of tin plate. The flux used contains no free acid, but is a perfectly neutralized solution of zinc chloride. This flux drys and cleans the base plate much more quickly than palm oil, and, as shown by experience, produces a plate equal in quality, pound for pound of coating, to any made by the palm oil process. All long ternes, and many of the grades of short ternes are made by this process. The lead-tin alloys generally used for short ternes have higher melting points than tin, hence higher temperatures are required than in tin-coating. The coating on terne plate is also much heavier than on coke tin plate, so that the lowest speed and the highest temperature practicable for the palm oil are required to give the lightest coated terne plate made, which is 8 pounds per box. For coats up to 15 pounds, spiral grooves are required in the exit rolls to get the thickness of coat desired, and for heavier coats redipping must be resorted to.

Combination Process: To provide for this redipping, combination processes similar to the combination processes used in manufacturing charcoal plates are employed. But the word redipped is of itself no guarantee that the plate carries a heavier coat, for the plate may be redipped by passing it through the machine a second time, when the coat would be no heavier than when passed through but once.

Finishing the Plate: The branner is similar to that used in making tin plate. For removing the excess oil, the canton flannel rolls are generally served with hard wood sawdust, to absorb the oil. In the case of oil finish plate, only a part of the oil is removed by the branning rolls, or it may all be removed in the branning rolls and another coat applied by means of cloth wrapped rolls succeeding the buffing rolls. In the case of dry finished plates, enough dry cleaner is employed to absorb all the oil, and the buffing rolls remove all the dust, leaving the surface of the plate dry and clean. Due to the nature of the lead in the alloy, terne plates do not have the bright lustrous appearance of tin plate, and due to the crystallization or the contraction of the alloy on cooling, the surface of the more heavily coated plates is covered by a ramification of more or less fine lines, dividing it into small areas almost uniform in size and shape. This marking of the surface is known as the mottle, and appears on plates carrying a coating of twelve pounds or more. At twelve pounds the mottle lines are very fine and are barely distinguishable, but they increase in width with the weight of the coating, so that an experienced observer can closely estimate the weight of the coating on new plate. Under certain conditions the original mottle is somewhat obscure on old plate. The fineness or coarseness of the mottle, that is, the size of the areas enclosed by the mottle lines, can be controlled by the rate of cooling, and are also affected by the presence of antimony in the terne alloy.

Assorting: As the sheets emerge from the buffing or oiling rolls, they drop upon a receiving bench provided with guards, where they are allowed to collect in piles or stacks. On account of their size, long ternes must be received and guided from the branner by hand. When a sufficient number of plates have been thus collected, they are trucked to the assorting room for final inspection, sorting, counting, and weighing. The assorting room is a well lighted building with the inspection tables or benches arranged along each side in front of the windows. The inspection and assorting are performed in one operation by women and girls, as in the case of tin plate. The plates are inspected on both sides and assorted into the four grades known as **primes, menders, strippers** and **scrap.** The primes include the sheets free from all visible defects that are injurious to the plate; menders are plates that contain defects in the coating that can be remedied by rerunning, that is, by passing the sheet through the tinning operations again; strippers correspond to seconds of the tin mill. Unlike tin plate, which is usually worked up into small articles or retinned after forming, thus permitting the use of the good parts of seconds, all heavily coated terne plates shipped must be primes, because the uses to which these plates are put generally require a full sized sheet. In the case of these heavily coated sheets, strippers are reclaimed by passing them through a flux tinning pot in which some of the coating is removed, i. e., stripped off, to form primes of a more lightly coated plate. Scrap, of course, are sheets that cannot be reclaimed, hence they are detinned by melting off the coating in a specially designed furnace, and the base metal is sent back to the steel mills as scrap. The defects that cause the rejections on terne plate are the same as those for tin plate. When the great number of times the plates are handled is considered in conjunction with the fact that 30 or 40 per cent. of the defects are attributable to defects in the sheet bar, the number of defective plates appears surprisingly small.

Reckoning: After the inspection, the primes are collected and, if short ternes, they are counted out, 56 plates at a time, as that number is all a man can handle easily, and placed on a scale for weighing. Two such lots are weighed together to make the box of 112 sheets, which are placed in a box with a slip showing the actual weight of the box. The base weight, the size, the weight of the coat, the finish, and the kind of steel in the base are stamped on the ends of the wooden box. All sheets made by the American Sheet and Tin Plate Company are then taken to another room where each is stamped under small presses with the customer's trade mark, if any, and the weight of coat carried by the plate, when they are replaced in the boxes. The covers are then nailed on and the boxes stored in the ware-house until such time as orders can be completed for shipment.

CHAPTER V.

MANUFACTURE OF STEEL TUBULAR PRODUCTS.

SECTION I.

HISTORY AND CLASSIFICATION OF STEEL TUBULAR PRODUCTS.

Events Leading to Lap-Weld Process: Although tubes have been used by man for several thousands of years, the use of iron or steel for making them is of comparatively recent origin. Primitive tubes were probably made of bamboo or wood. The Egyptians used earthenware tubes, and the Greeks and Romans made tubes of lead and bronze. In 1685 tubes or pipes made of cast iron were used in the construction of the water works at Versailles, France. Before this time, however, hollow cylinders of wrought iron or steel had been used in the manufacture of guns, and this industry was stimulated by the invention, in France of the flint-lock gun in 1640. Prior to 1812 the tubes, or barrels, for these guns were made by hand from plates which were first bent into cylindrical form, when the edges were overlapped, heated and welded together, piece-meal, over a mandrel. In that year Osborne, an Englishman, invented machinery for doing the bending and welding, but the method of manufacture remained fundamentally the same.

Events Leading to Butt-Weld Process: About the year 1815 William Murdock, a Scottish inventor, introduced at London the use of coal gas for lighting purposes. For conveying this gas, Murdock collected old musket barrels, which he screwed together to form continuous tubes for conducting the gas from his generators to the various points for burning. The popularity of this lighting system created a great demand for tubes, and stimulated inventors to seek some means of producing the tubes more rapidly and at lower cost. The first to succeed in this undertaking was James Russell, who filed patent papers describing his process as "an improvement in the manufacture of tubes for gas and other purposes" in 1824. In his method the plate was bent as formerly, but the edges were not lapped, and the tube was formed by butting the white hot edges of the bent plate together. The initial welding was done with a tilt-hammer provided with round grooves in the head, and the rough tube thus formed was finished by reheating it and passing it through a round groove in a rolling mill and over a mandrel which was supported in the pass, or opening, between these rolls. The next year, however, Russell's work was overshadowed by the invention of Cornelius Whitehouse, who succeeded in forming a commercially perfect tube by merely drawing the flat plate, heated to a proper temperature, through a "bell" or die. This invention, which became the basis of the present-day butt-weld process, made it possible to produce tubes of superior quality much more cheaply than ever before. Shortly

after this invention, about 1832, the first shop for making butt-weld pipe in the United States was established in Philadelphia by Morris, Tasker and Morris. Four years later this firm built the works afterwards known as the Pascal Iron Works. Following this success, other plants appeared in Eastern Pennsylvania, Eastern New York, New Jersey and Massachusetts, but no plants were built west of the Allegheny Mountains until after 1860.

First Seamless Tubes: Following these developments in making welded tubes, inventors turned their attention to the productionof seamless tubes. At first they attempted to duplicate with iron or steel the method used to produce tubes of lead and other ductile metals, namely, forcing the hot metal through an orifice formed by a mandrel or punch located and supported in the center of a circular die. In 1836 such a process was patented by Hanson in England, but his method proved impracticable. Two other methods were brought out in 1840 and 1845. They involved the cupping of a plate or the piercing of a round billet in a press, and subsequently elongating the rough tube thus formed by drawing or rolling. While practicable, these methods were costly, and for fifty years the use of seamless tubes was restricted on that account.

Innovations by Briggs and Bray: Besides these developments in methods of manufacture, two other events should be mentioned because of their far reaching effects on the industry as a whole. About 1862 Robert Briggs, then superintendent of the Pascal Iron Works, formulated the dimensions of pipe, or tube, threads, and compiled a table giving the nominal sizes, the exact diameters and the number of threads per inch for all sizes of pipe and tubes up to 10 inches. These formulas and tables were subsequently adopted as standard for the manufacture of all tubes and pipes up to 15 inches in size and are widely known as "Brigg's Standards," but the name now officially adopted is American Standard (Brigg's) Pipe Thread.[1] In 1887 Thomas J. Bray, Riverside Iron Works, Wheeling, W. Va., began making butt-and lap-welded pipe of soft Bessemer steel. Up to that time wrought iron had been the only material used for welded pipe and tube. Bray proved that steel was not only equal to wrought iron for this purpose, but actually superior to it in many respects.[2]

The Present Importance of the Steel Tubular Industry and of the steel tubular products is apparent to all observers. Starting in August, 1887, with Bray's trial lot of about 30 tons, the industry grew by leaps and bounds, until today the production of steel tubular products in the United States alone is close to, or exceeds, 3,000,000 gross tons. This growth was due to many things, chief of which is the diversity of uses to which steel tubular products may be and are applied. The mere mentioning of the

[1]For details of this standard see Bulletin No. 6., Correct Pipe Threading Principles, Published by National Tube Co., Pittsburgh, Pa.

[2]See "The Manufacture of Welded Steel Tubing," by Thomas J. Bray, Proceedings Engineers Society of Western Pennsylvania, 1888.

names, oil, gas, air, water, plumbing, heating, ammonia, dry-kiln, greenhouse, boiler tubes and bed-stead tubing are sufficient to call to mind industries almost wholly dependent upon steel pipe or tube. In addition to these uses, we find it in service as trolley poles, flag poles, lighting poles, railings, conduits, telephone and telegraph poles, automobile axle housings and many other items too numerous to mention here.

Classification of Steel Tubular Products: The many uses to which the steel tubular products have been applied have led to a great variety of products and to the use of a large number of more or less descriptive terms in designating the products used for different purposes. Use, therefore, may form a basis for classifying the steel tubular products, as shown in the following tables:

Table 102. Steel Tubular Products. Classified According to Use.

1. Standard Wrought Pipe.
    a. Standard Black Pipe.
    b. Standard Galvanized Pipe.
2. Heavy Wall Wrought Pipe.
    a. Extra Strong Wrought Pipe.
    b. Double Extra Strong Wrought Pipe.
3. Large Diameter Wrought Pipe.
    a. Water Mains.
    b. Gas Mains.
    c. Steam Lines.
    d. Penstocks.
    e. Dipped and Coated Pipe, etc.
4. Special Purpose Pipe.
    a. Air Line Pipe.
    b. Air Brake Pipe.
    c. Signal Pipe.
    d. Trolley Poles.
    e. Line Poles.
    f. Flag Poles, etc.
5. "Oil Country Goods".
    a. Casing.
    b. Oil Well Tubing.
    c. Drive Pipe.
    d. Rotary Drill Pipe.
    e. Gas Line Pipe.
    f. Oil Line Pipe.
    g. Working Barrels, etc.

Table 102. Steel Tubular Products—Continued.

6. Boiler Tubes.
   - a. Lap-Weld Boiler Tubes.
   - b. Seamless Tubes.
     - i. Hot Rolled.
     - ii. Cold Drawn.

7. Tubing.
   - a. Seamless Mechanical.
   - b. Bedstead, etc.

8. Cylinders.
   - a. Anhydrous Ammonia.
   - b. Carbonic Acid.
   - c. Oxygen.
   - d. Hydrogen.
   - e. Compressed Air.
   - f. Nitrous Oxide Gas.

Another classification is based on methods of manufacture. On this basis all steel tubular products may be placed under the two broad heads of welded and seamless, which in turn may be subdivided, as shown in the following table:

Table 103. Steel Tubular Products Classified According to Methods of Manufacture.

A. Welding Processes.

I. Butt-Weld Process.
(Pipe, ⅛ inch to 3 inches, nominal diameter.)

II. Lap-Weld Process.
(Pipe, tubes and tubing 1¼ inches to 30 inches, nominal diameter.)

III. Hammer-Weld Process.
(Pipe, 20 inches to 96 inches, nominal diameter.)

B. Seamless Processes.

I. Piercing Process.

1. Roll and Disc Piercing.
(Tubes and Mechanical Tubing up to 9 inches, diameter.)

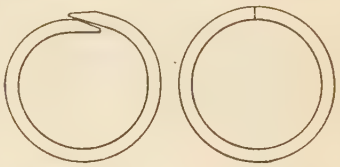
a. Hot Finished.
(1½ inches to 9 inches, diameter.)

b. Cold Drawn or Cold Drawn and Annealed.
(Any size up to 9 inches.)

Table 103. Steel Tubular Products—Methods of Manufacture—Continued.

II. Cupping Process.
(Pipe, tubes, and cylinders 6 inches to 20 inches, diameter.)
a. Hot Drawn (Finish).
(6 inches to 20 inches, inclusive.)
b. Cold Drawn (Finish).
(6 inches to 9 inches, inclusive.)

Modern Methods of Manufacturing The Welded Tubular Products: As indicated in the tables above, there are three methods of welding, known as butt-welding, lap-welding, and hammer-welding, or horn-welding. A butt-weld pipe or tube is made from a hot rolled strip, with square or slightly beveled edges, called a skelp, the width of which corresponds to the circumference of the pipe, and the gage to the thickness of the wall. By heating this skelp to the temperature where a **natural flux** forms on the skelp in the furnace, and drawing the skelp through a suitable die while at this temperature, the skelp is bent into cylindrical shape and its edges pressed firmly together into a **butt-or jump-weld,** thus forming a pipe. In the **lap-weld** process, the edges of the hot rolled strip, or plate, which must be of a gage corresponding to the thickness of the wall of the pipe desired but of an overall width slightly greater than its circumference, are first **scarfed,** that is, beveled or tapered, to form acute angles with the faces. Before welding, this scarfed strip or plate is bent into a cylindrical form with the scarfed edges overlapping, so that a much larger surface for welding is provided than is the case in butt welding. After heating to a welding temperature, the lapped edges are welded together by passing over a mandrel between two rolls. In the **hammer-welding** process, the plate, whether scarfed or not, is bent into the cylindrical form, after which its edges are lapped, then heated and welded together with a suitable hammer and anvil. Each method has practically its own field. The first method can be employed for sizes ranging from one-eighth inch to three inches; the second method may be applied to sizes ranging from one and a quarter inches to thirty inches; while the third method is used regularly to weld pipe twenty to ninety-six inches in size.



Lap-Weld Butt-Weld

Fig. 277. Showing the two different methods of forming the seam.

The Seamless Products are made by two basic processes known as the **piercing** and **cupping** processes. The piercing process, in which a solid round bar or billet is pierced and afterwards brought to the desired diameter and thickness, is employed generally on sizes up to nine and one-

half inches, while the cupping process, in which the tubing is formed by pressing a solid round plate through cup-shaped dies, may be employed for all sizes between five and one-half and twenty inches. The reasons for these restrictions in the use of the five methods cited will be made apparent in the detailed descriptions that are reserved for succeeding sections.

Pipe: Referring to the classification of the steel tubular products based on uses, we observe that a large number of products were classed as **wrought pipe.** Applied in its most general sense, pipe is a term that designates any long hollow body used for conducting gases or liquids, and may be of clay, cement, wood, lead, brass, cast iron, or steel. Restricted to the steel industry, the term is one that is applied to all tubular products intended for the purposes such products are ordinarily used, as for conducting water, fuel gas, steam, air, oil, etc. The term wrought merely distinguishes it from cast iron pipe.

Varieties of Pipe: Since the pipe should be adapted to the kind of service it is expected to give, there are different varieties of pipe. Thus welded pipe is regularly made in three separate classes which are distinguishable by characteristic differences in wall thickness of each class of pipe as a class; these classes of pipe are known as standard, extra strong, and double extra strong. Standard pipe is pipe made and threaded to the American Standard (Briggs). The weights or wall-thicknesses of this pipe are suitable for all ordinary purposes, such as plumbing, water and gas lines, steam lines, etc. Extra strong pipe is characterized by heavier walls in all sizes than the standard pipe, and is used where higher internal pressures or greater column loads are to be sustained. Double extra strong pipe is used for extremely high pressure purposes, such as hydraulic lines for operating hydraulic machinery or apparatus. Line pipe, used for the higher pressure oil, gas and water lines, and drive pipe, used in drilling oil and water wells, differ from each other and from standard pipe mainly in the manner in which the different sections of pipe are coupled together. Air line pipe, used for steam train and electric car air-brakes, and drill pipe, used for oil, gas and water well drilling by the rotary system, are further examples of the different varieties of pipe. In addition to these varieties, pipe is also made to conform to the English Standards. Welded pipe may be used for many structural purposes, such as columns, railings, piling and poles for telegraph, telephone and electric power lines, also railway signal and safety devices.

Sizes of Pipe: As a whole, pipe is made in sizes that range from $\frac{1}{8}$ inch nominal inside diameter to 96 inches outside diameter. Up to a diameter of 12 inches, pipe is commonly known by the inside diameters, and is spoken of as three-quarter-inch-pipe, one-inch-pipe, two-inch-pipe, etc. These terms are but nominal, because, in order that different pieces of pipe may be coupled together conveniently, the outside diameters must be standardized, and any variation due to differences in gage, or thickness of the wall, occurs in the bore. However, care is taken to make these

differences for any one kind of pipe as small as possible, so that in the case of standard pipe these nominal diameters approximate closely the actual inside diameters. Exceptions may be cited in the case of 8-inch, 10-inch and 12-inch standard pipe which are made in different weights to adapt the pipe to different purposes. For example, 8-inch standard pipe is made in two standard weights, namely 24.696 lbs. per foot and 28.554 lbs. per foot, the difference in weight being represented by increased wall-thickness. Standard pipe, line pipe, drive pipe and extra strong pipe over 12 inches internal diameter and practically all pipe over 15 inches in diameter are known by their outside diameters.

Casing is the term applied to all pipe used to provide a casing, or wall, for oil and gas wells. It is known by its inside diameters, and ranges from 2 inches to 15½ inches in size. Originally, its walls were always somewhat lighter than those of standard pipe, but some casing is now made nearly as heavy as extra strong pipe.

Tubes: In America the use of the term tube is somewhat restricted. It is quite generally applied to seamless products, though these may be used for various purposes, and it is always used in referring to the heat transferring pipes of steam boilers, which are known as boiler tubes. In tubular boilers, these tubes serve as flues for conducting the products of combustion from the fire box to the chimney, but in water tube boilers the tubes are filled with water which absorbs the energy from the hot gases as they pass over and outside of the tubes on their way to the stack. In tubular boilers, the tubes are supported by tube sheets at each end of the boiler. The ends of the tubes extend through close-fitting holes in the tube sheet and are expanded or beaded therein, then secured with ferrules or by autogenous welding. In water tube boilers, the tubes usually extend between headers, into which they are fastened as into tube sheets. Boiler tubes may be either welded or seamless and are known by their nominal or their exact outside diameter, as may be specified. In England the term tube is applied to all the steel tubular products.

Tubing may be either welded or seamless. Among the welded products, bedstead and mattress tubing and oil well tubing may be mentioned. Bedstead tubing is known by its outside diameter and its weight per foot as specified; it differs from standard welded pipe in that its wall is somewhat lighter and its surface is freed from scale to make it suitable for enameling. Oil well tubing is known by its inside diameter. With some exceptions, such as seamless boiler tubes, bailer tubes for oil, gas and water-well drilling, etc., the term tubing is applied to practically all seamless products. These products may be, and are, used for so many different purposes it is undesirable to attempt to enumerate them here. Suffice it to say, those products fall into two classes, namely, internal pressure tubing, such as cylinders for containing gases or liquids under pressure, superheater pipes,

etc. and mechanical tubing, used for structural purposes and to form certain parts of machines, such as axles, drive shafts, housings, etc. Seamless tubing is known by its nominal or its exact outside diameters, as specified, and is made in sizes from ⅛ inch to 20 inches. In the descriptions of the seamless processes given herein, the term tube is often used to designate a single piece whether of tube or tubing.

Kinds of Steel: For seamless products only electric or open hearth steel of high quality can be used, but this steel may be carbon steel of any carbon content or alloy steel of any structural grade. For butt- and lap-welded tubular products the presence of too much carbon or sulphur or traces of certain alloying elements, such as nickel and chromium, must be guarded against. For the manufacture of ordinary pipe and casing, either a dead soft basic open hearth steel or a Bessemer steel of welding quality may be used with about the same success, though many pipe makers claim that Bessemer steel welds a little better than the basic open hearth steel. Owing to its higher phosphorus content, the Bessemer steel is somewhat stronger than the basic open hearth steel, but it is still sufficiently ductile to meet the most exacting demands that may be made of ordinary pipe. On the other hand, because of its greater ductility and freedom from certain impurities, the basic open hearth steel is more desirable for some purposes than the Bessemer. These facts, together with certain other advantages, has led to the use of Bessemer steel almost exclusively for common grades of pipe, and to the use of open hearth steel in special grades of pipe, boiler tube and seamless products.

Skelp: The steel from the converters or open hearth furnaces is cast into ingots and, with one or two exceptions, is rolled on blooming and slabbing mills into rectangular blooms and slabs by the usual methods. After the usual discard to eliminate ingot defects, the acceptable portions of the blooms or slabs are sheared into specified lengths and taken to the skelp mills. As now employed, the term **skelp** is applied to all flats that are to be used in the manufacture of butt-welded pipe. The word is derived from an old time process known as **skelping,** or **piping,** an operation whereby the strip or plate was bent into the form of a split cylinder with overlapping edges preparatory to lap-welding. This operation was performed with a machine called a "crocodile" or "skelper." It consisted of a long semicircular metal trough, over which the flat was laid, and into which it was pressed by means of a long, round-faced die, thus bending the strip into a U-form that was in turn bent into a circle by a separate operation. Therefore, in the case of lap-welded pipe, the term skelp is not, in the parlance of the pipe and tube mills, applied to the plates until after they have been bent into the rough tubular shape preparatory to welding.

SECTION II.

BUTT-WELDED PIPE.

Rolling the Skelp: Skelp for butt-welded pipe may be rolled on any mills adapted to the rolling of long thin flats. In the case of the smaller sizes of pipe, ⅛ in. to ½ in., the skelp sizes will range from about .4 in. to 1.57 in. in width and from .068 in. to .109 in. in thickness. For the larger sizes of butt-welded pipe, the skelp will range in width from 3 in. to 11 in., and in gage from .113 in. to .216 in. for the standard, or from .154 in. to .300 in. for extra strong pipe, and from .308 in. to .600 in. for the double extra strong. While it is evident that this material may be rolled by means of tongue and groove passes and plain rolls, much in the same manner that sheet bar is rolled, on many different types of mill, yet, on account of the introduction of special features aiming at improvement in the quality of pipe, skelp is best rolled on a mill specially designed for the purpose.

Example of a Skelp Mill: As an example of a modern skelp mill, the No. 5, 13-inch mill at the Lorain Works of the National Tube Company may be cited. This mill consists of thirteen stands of horizontal rolls and one stand of vertical rolls arranged on the continuous plan, but the roll stands are so placed that the piece will clear the second, fifth, seventh, tenth, eleventh, twelfth and thirteenth passes before it enters the next succeeding passes, respectively. In order to secure this arrangement, the first ten stands are set up in four tandem groups composed of two, three, two, and three stands, in the order named. The stands in each group are geared together and driven through one shaft. The eleventh stand, in which the rolls are vertical, and the twelfth, thirteenth and fourteenth stands, which are horizontal rolls, are separately driven. The mill is served by a continuous heating furnace and is provided with a hot shear between the fifth and sixth passes, that is, between the second and third groups of rolls. Its product is received on a two-way cooling bed. An end-cutting shear is located at each of the two delivery corners of the cooling bed, and between these two shears is placed a third, known as the clipping shears.

The Operation of the Mill: The bloom, which is rectangular in shape and of the proper dimensions to produce skelp of the desired size, is heated in the continuous furnace to a rolling heat. The first stand of rolls is placed far enough from the furnace to permit the switching of the bloom to the mill floor in case there should be a rolling accident on the mill or in case the bloom should be overheated or underheated. The first

two or four stands in the mill, corresponding to roughing rolls in other mills, are used to Spellerize the metal. In the usual manner of carrying out this process, the working surfaces of the first and third stands, called **knobbling rolls,** are provided with regularly shaped projections and depressions about ¼ inch in height, while the surfaces of the second and fourth passes are plain. When the bloom passes through these rolls, the **roll-knobbling,** or kneading, process to which its surfaces are subjected is said to give a pipe surface that is better adapted to resist corrosion in the form known as pitting than that of skelp rolled on plain rolls only. Upon leaving the Spellerizing rolls, the bloom, now much reduced in thickness, is edged by means of a twisting guide in the second group of rolls, in order to control the width. It is then cut into two or more pieces by means of the hot shear, in order to adjust the length of the finished strip to the cooling bed. These pieces then pass flat-wise, or flat-and edgewise if desired, through the next five stands to the vertical rolls. These rolls are grooved to roll the edges of the skelp, which must be slightly beveled, so that, when the skelp is bent to form the pipe, they will fit squarely together and form a perfect joint. In this way, the defects in pipe known as a falling, or sunken seam, a depression along the weld on the outside of the pipe, and a deep seam, a depression on both the outside and inside, are avoided, for both may be due to round edges on the skelp. To secure the required edge on the finished skelp, the bottoms of the grooves in the vertical rolls are made slightly convex, thus forming concave edges on the skelp, so that the spreading of the steel in the succeeding passes through the three stands of plain rolls will be just sufficient to fill the concave surface.

Shearing the Skelp: From the finishing rolls of the mill, the skelp passes over the cooling bed to the shears, where the crop ends are cut off, and the remainder of the strip is cut into the lengths desired, the standard lengths being twenty feet for singles and forty feet for doubles. The skelp is then passed to the clipper, a machine that performs the double function of a shear and a press. It shears from one end of the skelp two small triangular shaped pieces, one from each corner, shapes, or cups, the pointed end to start the curve for welding, and bends the skelp transversely just back of the curve, so that when the skelp lies on the flat surface of the welding furnace hearth the pointed end will be elevated, thus making it easier to grasp it with the welding tongs. Care is required in adjusting the ends of the strips in this machine, so that the clipping and cupping will be symmetrical, as otherwise the skelp will be liable to stick in the welding bell, which will be described later. The skelp is now stacked in small piles, loaded on railroad cars with a crane, and then taken to the butt-welding furnaces.

The Butt-Welding Furnace: In the pipe mill, the skelp, except in the cases of very small and of extra strong pipe, is charged directly into

a reheating furnace preparatory to welding. In order to secure uniform heating of the material, a condition absolutely necessary to effect good welding, and economize in time and labor, factors that vitally affect the cost of pipe, the heating furnace, charging apparatus, welding appliances, and finishing machines must be of special design and constitute a single unit. The heating furnace, which of necessity must be stationary, is the central figure in this unit. These furnaces are of the producer gas fired regenerative type, and, depending upon whether they are designed for single or double lengths, are 26 or 44 feet long inside, but vary in width to suit the different sizes of pipe, in order to accommodate a certain number of skelp strips, which lie side by side upon the hearth, or bottom, of the furnace. Special care must be taken in making up the hearths of these furnaces in order to prevent the material of the bottom from sticking to the hot skelp and thus ruining the pipe. The materials used for this purpose are high grade sand, gravel and unglazed chinaware, the latter being placed upon the sand. The gas and air for combustion are admitted through ports arranged along the sides of the furnace, so that the flame must pass transversely over the hearth, which is covered with a low, arched roof. The ends of the furnaces are constructed so that only narrow openings, one extending across each end just above the level of the floor, remain to provide an inlet and outlet for charging and drawing the skelp and repairing the hearth. When the furnace is in operation, these openings may be almost or entirely closed by means of adjustable shields suspended by proper supports from above. Opposite the inlet, is placed the charging machine, while the welding machine is opposite the outlet. Both machines are mounted on wheels. Those under the charging machine run on tracks laid across in front of the furnace, and the machine is propelled back and forth as desired by electricity. Usually, only the end of the welding machine next to the furnace is movable, and it is moved back and forth by means of a steam or air cylinder. The charging machine for the larger sizes of pipe is provided with a platform for the operator to stand upon, a table for supporting a pile of skelp at a convenient level, and, along side, an electrically operated endless chain pusher for charging the skelp into the furnace. Skelp for pipe up to ¾ inch in size may be charged by hand, in which case a charging machine is replaced by a stationary table, located at one end of the furnace, for supporting the strip convenient to the workman.

The Welding Machine very much resembles a draw bench, with the end next the furnace mounted on wheels and the farther end pivoted. It consists of a carriage, on which is mounted an endless chain, for drawing the skelp from the furnace through the welding die, and a stop for holding the welding die as the skelp is drawn through it. The draw chain is actuated by means of a motor-driven sprocket wheel on the pivoted end. The welding die, called a welding **bell** on account of its form, is so shaped inside

that, as the skelp is pulled through it, the strip is gradually bent into the form of a tube, and its edges are forced together, thus forming the weld. The bells are made of a special grade of cast iron.

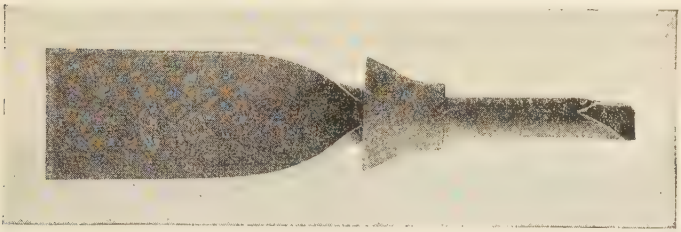


Fig. 278. Showing how the Skelp is Bent and Welded as it is Drawn through the Welding Bell.

Operation of the Butt-Welding Furnace: The skelp from the rolling mills in either single or double lengths, depending upon the size of the furnace, and of a width and gage to make the pipe desired, is unloaded from the flat car, bundle by bundle, and placed upon the charging machine by an overhead crane. Starting at one side of the furnace, the skelp with the clipped ends foremost, is slid by hand from the pile to the charging table, one strip at a time, and pushed, with the convex side of the clipped end up, into the furnace. After charging each strip, the machine, if one is employed, is moved over a distance corresponding to the width of the strip before pushing in another. In this way the bottom of the furnace is soon covered with the strips lying side by side, and the charging machine is now ready to repeat the cycle. Since the size of the furnace and the rate of charging are so regulated that, when the last strip has been charged, the first one charged will have reached the welding temperature of about 1450° C., the welder now begins drawing the skelp in the same order it was charged. This he does by means of a specially designed tongs, having short jaws for grasping the pointed end of the skelp and very long handles with a locking bend in the middle and a knob on the end for engaging with the lugs, or the dog, on the draw-chain. No section of these tongs can be larger than the outside diameter of the pipe, as they must pass through the welding bell. Preparatory to drawing each strip of skelp, the welder grasps the pointed end of the skelp with the jaws of the tongs. He then slips, large end first, a welding bell of the proper size over the handles of the tongs and drops the handles between the two prongs of the bell stop in such a manner that the dog on the draw-chain will engage the knob on

the handle. Then, the chain, traveling continuously away from the furnace, draws the tongs, bell and skelp out of the furnace. When the bell reaches the stop, it is held there until the skelp has been drawn through for its full length, when the bell drops from the stop by its own weight. The flat skelp is thus bent into the form of a pipe, and its edges are forced together and welded, all in the one operation. In this way the welding requires but little time: one inch pipe, for example, may be welded at the rate of 250 twenty-foot lengths per hour. For the larger sizes of standard pipe, two welding bells, instead of one, are employed.

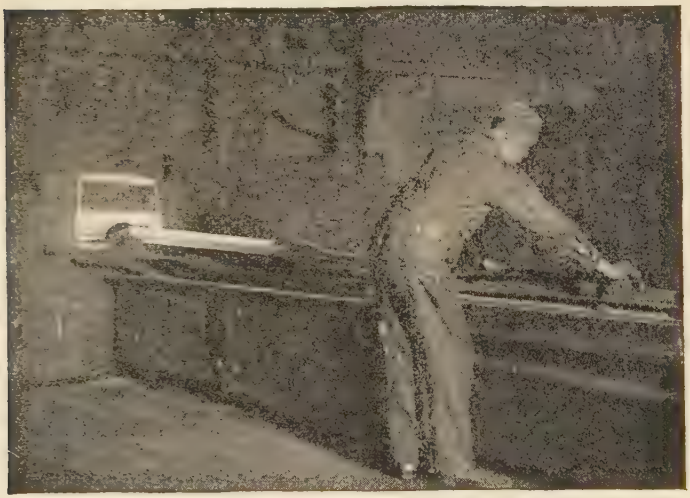


Fig. 279. Butt-Welding Furnace, Showing a Pipe in the Process of Being Welded.

Welding Small and Extra Strong Pipe: This procedure applies to pipe of standard thickness and of the more common sizes, and must be varied to suit conditions in welding other pipe. For the smallest sizes and double extra strong pipe, used in the construction of hydraulic machines, tongs cannot be used, because in the one case, the smallness of the bell will not permit tongs large enough to be sufficiently strong for drawing to be used, and in the other, the skelp is too heavy to be securely grasped with tongs. Furthermore, if it were attempted to form this heavy-walled pipe in one operation, the pull would be so great that the tensile strength

of the material at the high temperature for welding, would be exceeded. The skelp for these pipes is, therefore, tagged, that is, a round bar of steel is welded to the clipped end before it is charged into the furnace, to take the place of the tongs. The drawing is then conducted as outlined above, except the skelp is charged by hand into the furnace at the drawing end of it. The skelp for double extra strong pipe is drawn through several bells of decreasing sizes, being reheated prior to each pass.

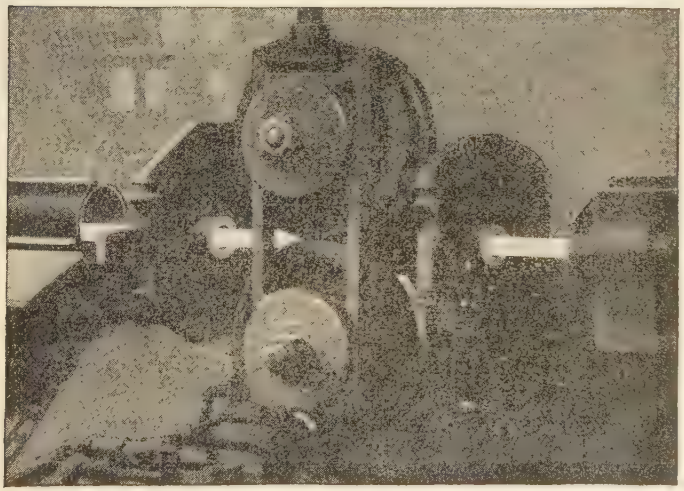


Fig. 280. Showing Pipe Passing through the Sizing Rolls.

The Hot Finishing of Pipe—The Sizing Rolls: When the pipe has been drawn through the welding die, the tongs are removed, and the pipe at once moves down a slightly inclined table in front of the sizing rolls. These are electrically driven horizontal rolls of cast iron, 18 in. to 24 in. in diameter, depending upon the size of the pipe to be made. They are grooved to form a perfect round, when properly adjusted, of the exact outside diameter of the pipe desired. The rolls contain usually but a single groove, hence are very short and are supported in a single two-high housing. In passing through these rolls the pipe, which was purposely drawn slightly oversize, is compressed and elongated to an exact uniform outside diameter, and the weld is also improved to some extent thereby.

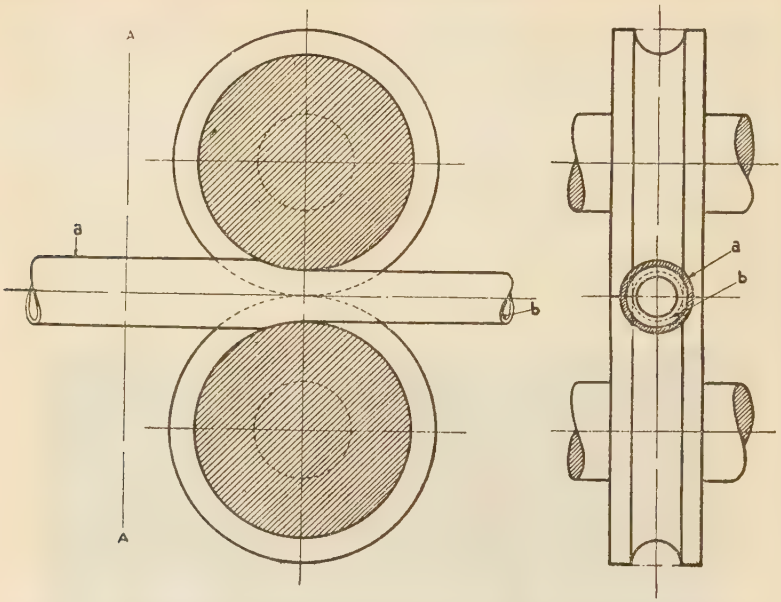


Fig. 281. Sizing Rolls. Illustrating how the size of the Pipe is Reduced to the Diameter desired.

The Scale-removing Machine: The heating of the skelp in the furnace results in the formation of a fluid flux, or scale, which, after hardening by cooling is called welding scale. This scale is not removed from the inside of the pipe by the welding and sizing processes, and forms a coat like a heavy hard enamel shortly after the pipe is welded. The National Tube Company have devised a means of removing this scale and also that formed on the outside of the pipe after welding. Therefore, the pipe from the sizing rolls is slowly transferred over a specially designed cooling table to a set of rolls known as breaking down or scale-removing rolls. This set of rolls may consist of two stands of two-high horizontal rolls in tandem, set some eight or ten feet apart, or of two such stands and a stand of vertical rolls placed between the horizontal rolls. The grooves in these rolls are so formed and the rolls so adjusted that the pipe is slightly compressed and elongated in the first or the first and second stands, and brought to correct and uniform diameters in the last stand. The pipe is delivered to the scale-removing rolls over the cooling table, which is slightly inclined, by means of lugs placed about 20 inches apart on endless chains. These lugs cause the pipe to roll up the table so that it is uniformly cooled. The speed of the chains and the length of the table are adjusted to remove the pipes as rapidly as they may be delivered from the sizing rolls, and deliver them to the feed table or trough in front of the scale-removing

rolls at a temperature just above the critical range, while the scale is hard and brittle but the pipe is still soft and ductile. The pipe then passes immediately into the rolls, where the slight deformation breaks the scale from both the inside and outside surfaces of the pipe. Since the pipe is

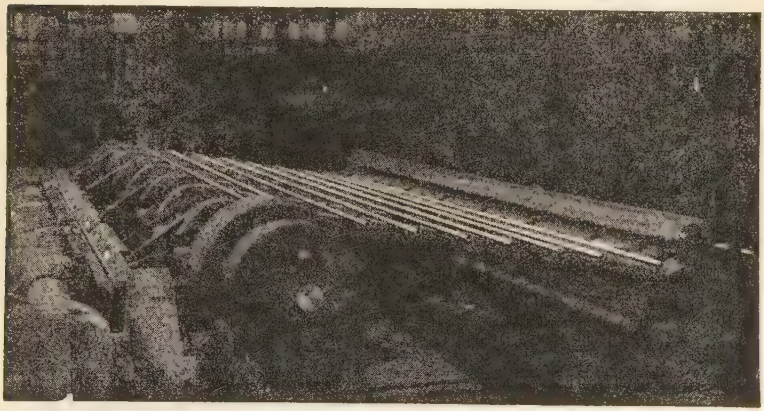


FIG. 282. Transfer Table over which the Pipe passes from the Sizing Rolls to the Scale-removing Rolls.

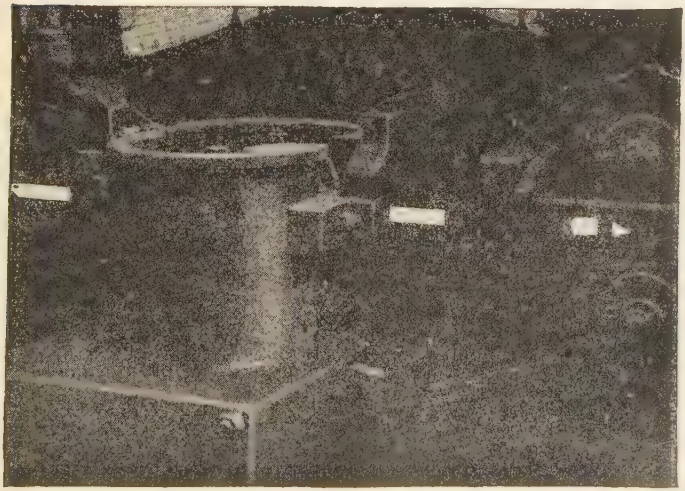


FIG. 283. Showing tube passing through Scale-removing Rolls.

delivered from the rolls below the scale forming temperature, only a thin film of oxide forms, and a pipe practically free of the heavy welding scale results, but the pipe is still bluish black in appearance, due to this thin film of oxide. Aside from the evident advantage of scale-free pipe in

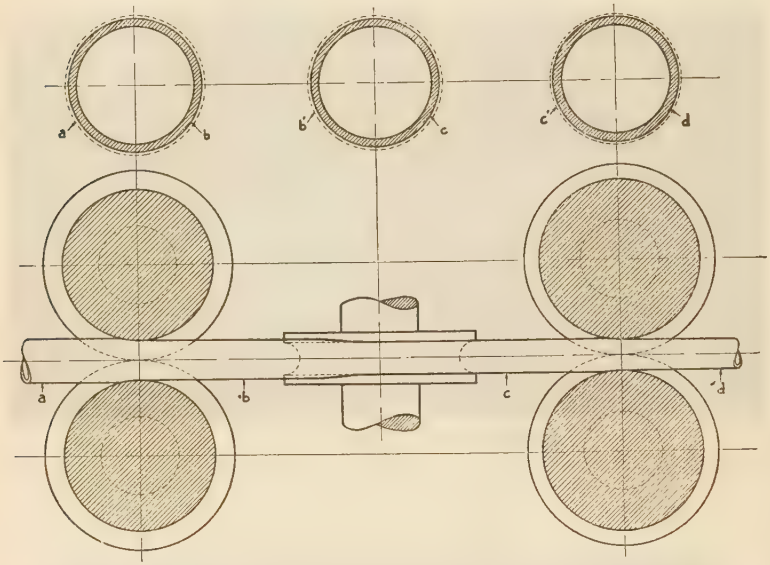


FIG. 284. Sketch illustrating action of the Scale-removing Rolls. In actual practice, the pipe is not reduced in size as much as shown in the diagram, which exaggerates the case for the purpose of illustration.

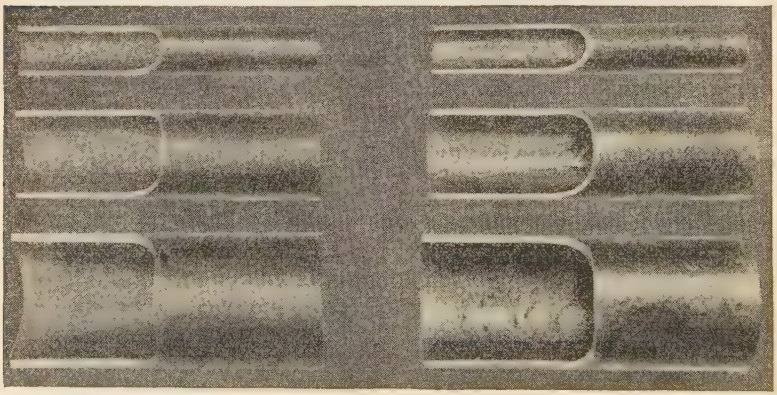


FIG. 285. Showing Pipe Finished without passing through Scale-removing Rolls (right) and after passing through Scale-removing Rolls (left).

actual service, the benefits of the scale removing process are especially noticeable in galvanizing. Much less acid is consumed in pickling for galvanizing, a smooth surface perfectly free from scale is obtained and all defects in the coating due to adhering scale are avoided.

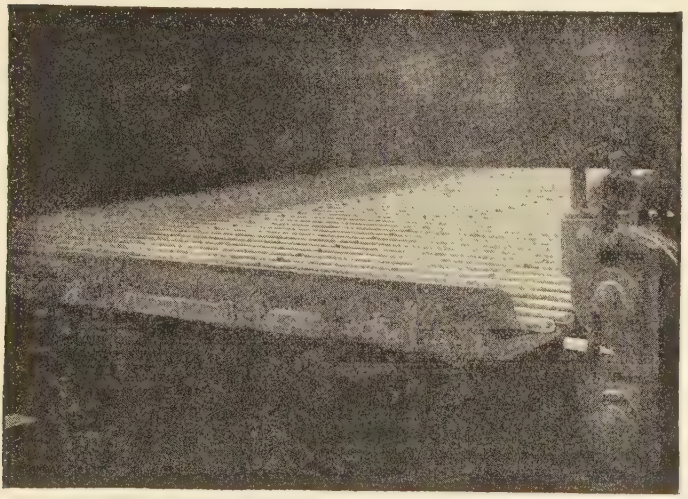


FIG. 286. Pipe passing from Scale-removing Rolls to Cooling Bed. This bed is designed to cause the pipe to cool practically straight.

Straightening Rolls: From the scale-removing rolls, the pipe is transferred over another cooling table to a set of straightening rolls known as the **cross rolls** (see Fig. 292, p. 1053). These rolls, electrically driven, are two in number, from two to four feet long and from ten to twenty inches in diameter, depending upon the size of the pipe to be straightened, and are set with their axes askew, so that they cross each other, forming an angle usually of about 30°, with their center points directly opposite each other. The bodies of these rolls are formed to give concave surfaces so that, when they are properly adjusted, a pipe lying between them is in contact with the rolls for their entire length. With these rolls revolving rapidly, the pipe, which is inserted between them endwise, is grasped by the rolls, rapidly revolved, and slowly drawn forward at the same time. The pipe emerges from the rolls practically straight, and moves forward on live rollers a short distance, where it is dropped laterally into a cradle or rack. In the case of double lengths, such pipe as is desired in single lengths is picked up by fingers attached to slowly revolving wheels, placed on a saw block

and sawed through at the middle before they are dropped into the rack. When a quantity of pipe weighing about four tons has collected in the rack, it is picked up by an overhead crane, dipped into water at an angle to complete the cooling and remove loose scale, and transferred to the cold finishing department; or it may cool in the air, in which case the loosened welding scale is blown out with compressed air.

Cold Finishing—Cutting and Inspection: In the cold finishing department, the pipe is delivered to the cold saws, which cut off the crop ends. From the saws the pipe is next transferred in bundles by overhead crane to the inspection table, where, by means of extension lights, it is given a thorough inspection for visible defects, such as crookedness, bad seams, open welds, laminations, blisters and rough surface spots. All these defects are plainly marked with chalk on the pipe itself, which is sorted into five piles, known as perfects, bends, recuts, middlecuts, and scrap. Bends are crooked pipes that may be straightened on a small gag press or with bending rolls; recuts are pipes that have defects near the ends, such as an open weld, and can be made perfect by cutting off a short piece from the end; while middle-cuts have, near the middles, slight defects that may be cut out, leaving the acceptable pipe in two short pieces.

Threading: The perfect pipe is now taken to the threading machines. The threading of the pipe is a matter that is given a great deal of attention, for without good threads a good fit between pipe and coupling is impossible. On account of its ductility, homogeneous composition and structure, the steel used for pipe cannot be nicely threaded with the old time die, the chasers of which were designed to push, rather than shave, the metal off. But although pipe steel is somewhat tough, it is easily and properly threaded with dies of modern design. The chasers of such dies are lipped to give a good cutting angle, as on a properly designed lathe tool. As a very complete treatment of pipe threading principles is given in bulletins published by National Tube Company, covering various features developed in commercial practice and in the company's own mill experience, this matter need not be taken up in detail here.

Testing the Pipe: From the threading machines, the pipe is moved over a transfer table to the testing machine. On the way, the threads, if the pipe is threaded, are **doped**, that is, covered with a non-hardening mixture composed of white lead, tallow, and graphite; the couplings, if any, are screwed as tight as may be by hand, and then, if the pipe is of large size, the coupling may be tightened by a machine designed for the purpose. The coupling is attached to one end of each piece of threaded pipe, and, on certain sizes, a thread protector is screwed on the other end. Unless otherwise desired, the pipe is then oiled by dipping it into a shallow trough of oil. The pipe is now tested by applying, internally, a hydrostatic pressure, which, for butt-weld pipe, varies from 700 to 2200 pounds per

square inch, according to the kind of pipe, the size of pipe, and the use to which it is to be put. For this purpose a specially designed machine is provided. It consists of a bench with a water tight head connected with a hydraulic line mounted on one end and a similar head, made adjustable to suit different lengths of pipe, mounted on the other, while a number of clamps for supporting the pipe and usually a small air hammer for tapping the pipe during the test are mounted between these heads. In testing, the pipe is adjusted between the heads, the supporting clamps are applied, the adjustable head is moved forward, pressing the ends of the pipe tightly against the packing rings, or leather gaskets, and the valve is opened, admitting water until the gage attached to the hydraulic pressure head show that the required pressure has been reached. This pressure is maintained for several seconds, during which time the pipe may be jarred with a hammer, if such a test is specified. For this purpose the face of the air hammer is brought to bear upon and vibrate against the pipe, which is thereby subjected to impact and vibration while under the maximum internal stress, a condition that adds a great deal to the rigidness of the test. The pipe is then unclamped from the testing machine, and one end is suddenly elevated while the water flows out, thus carrying out all flakes of detached scale with it. Each piece of pipe is then measured, and the measurements recorded, or tallied. If between ⅛ and 1½ inches in size, it is bundled, or, if over 1½ inches, it is usually stenciled, then weighed, the weights of the separate bundles or pieces being recorded. This done, the pipe is ready for shipment.

SECTION III.

THE LAP-WELD PROCESS.

Rolling Lap-Weld Skelp—Large Sizes: Skelp for lap-weld pipe, which ranges in size from 1¼ to 30 inches in diameter and requires plates from six to ninety-six inches in width, must be rolled on different mills, each adapted to certain sizes. For pipe over eight inches in diameter, the skelp is rolled on sheared plate mills. With proper care in heating, the use of salt or other scale removing materials is not necessary during the rolling of the skelp, since the reheating for welding forms a heavy coat of scale in any case. In side shearing the plates, more than ordinary care is necessary to see that they are cut to as near exact widths as possible. This cutting is accomplished in the plants of the National Tube Company by means of a double rotary shear that trims both edges of the plate at the same time. Since the distance between the two opposite sets of shear discs may be very accurately adjusted and cannot vary, the width of the plate is accurate and uniform. Care must be exercised to feed the plate squarely into the shear, a feat that is facilitated by the use of a large electro-magnet suspended over the entering table and supported on a movable truck or frame. After the plate has been laid out, the ends are cut off with an ordinary plate shear

of the guillotine type, and delivered over a roll table to the rotary shear. Here, with the plate resting in the correct position for shearing, the magnet is run back to the end farthest from the shear. When the current is turned on, the magnet attracts the plate and holds it firmly to a straight course parallel to the shear line laid out. Skelp for pipe from four to eight inches in size is rolled on the universal mill. With some few minor exceptions, the mill practice for skelp does not differ materially from the procedure already described for rolling universal mill plate. It is evident that spellerizing skelp on these mills would be very difficult, and since the wall thickness is so much greater, there is less need for it than in the case of the thin-walled small pipe. The scarfing of this large skelp is done at the pipe mills and will be described later.

Rolling Lap-Weld Skelp for Small Pipe: Skelp for pipe from two to four inches in size is rolled on a great variety of mills. The twenty-eight-inch reversing mill of the National Tube Company's Lorain Works is cited here because it is of a type almost unique among American strip and plate mills. It consists of two stands of two-high rolls in train, which are driven with a reversing engine, and a separately driven two-high stand of finishing rolls, which are immediately preceded by a stand of vertical rolls. However, when there is an outlet for great tonnage, the continuous type of mill, such as the one already described in connection with butt-weld pipe, is best adapted for rolling skelp of this size. As an example of such a mill the 16-inch mill at the National Works of the National Tube Company may be cited. This mill, arranged on the continuous plan, consists of ten stands of horizontal rolls and one stand of vertical rolls. The first nine stands of horizontal rolls are arranged in three groups of three stands each, with the vertical rolls immediately preceding and forming a part of the third group. The groups are placed far enough apart to permit the piece being rolled to clear each group before it enters the next one, but the stands in each group are geared together in the usual manner for continuous mills, so as to be driven from a single shaft. A tandem compound engine, located to one side of the third group, drives all three groups, the rope drive being employed to transmit the power and regulate the relative speeds of the three groups. Located at a distance of about 140 ft. beyond these rolls, is the finishing stand, which is separately driven by a small tandem compound engine, a rope transmission being employed to secure the proper speed of the rolls. A specially designed flying shear is placed about ten feet beyond the finishing stand, and a skelp, or plate, piler is located at a suitable distance beyond this shear. The mill is served by four continuous heating furnaces.

Rolling the Skelp: The billet, which has been previously inspected for harmful surface defects, is heated to the proper temperature for rolling, and is discharged from the heating furnace directly upon a roller table that carries it to the mill. Since the billet is pushed off the skids at a

height of four or five feet above the roll table, the fall breaks off the greater portion of the loose heavy scale formed in the furnace. The billet thus enters the first stand of rolls with a clean surface. A gate in the side guards of the table provides a means of throwing out any billets, which on account of improper heating, bad surface, or other cause, should not be sent through the mill. The first four stands of rolls are employed to Spellerize the metal, the first and third of which are the knobbling rolls. In these rolls the spreading of the metal is controlled by means of tongued and grooved passes. After passing through the fifth and sixth stands in the second group, the piece enters the vertical rolls of the third group which are used to control the width to a limited extent and to roll the edges. In passing through the three horizontal rolls of this group, the surfaces of which are plain, the piece is reduced to within a small fraction of the thickness desired before passing to the finishing rolls. The scarfing on the edges of the plate are rolled in on the finishing pass. As the skelp leaves the finishing pass it is automatically cut into proper lengths by the flying shear, carried forward by a roller table to a piling machine, and collected in stacks of forty pieces or more. A shear tender diverts the crop ends and any strips that contain noticeable defects to the scrap pile before they reach the piler. The stacks of perfect strips are picked up by an overhead crane, loaded on flat cars side by side and taken to the tube mills.

Steps in Manufacturing Lap-Welded Pipe: After the rolling of the skelp, at least eight more steps are necessary in the manufacture of lap-welded pipe by modern methods. These steps, in order, are scarfing, if the scarf has not been rolled in, bending, welding, sizing, straightening, cutting, jointing, and inspecting. As the apparatus for performing these operations must be varied somewhat to adapt it to different sizes of pipe, it is assembled in units, and each unit is adapted, therefore, to produce a certain range of sizes only. These units are sometimes referred to as lap-weld mills, or, more often, as lap-weld furnaces. While the arrangement and equipment of lap-weld furnaces are subject to considerable variation, the following description is typical of modern practice.

The Bending Furnace: In order to facilitate the bending of the strip or plate preparatory to welding, it is heated to a red heat, 700 to 800° C. in a furnace known as the bending furnace. This furnace is rectangular in shape, and is covered with a low roof, arched from side to side. As to length, these furnaces are built in two sizes, known as singles and doubles, the former being from 22 to 26 feet long inside to accommodate the more common lengths, and the latter some 44 feet to admit the heating of plates for double length pipe. The widths of the furnaces vary with the different widths of plate or strip and the methods of charging it. They are of the regenerative type, and are fired with gas, usually producer gas. The checker chambers are directly beneath the furnace, and the up-and-

down take flues for gas and air are distributed along each side. Low bridge walls separate these flues from the hearth, over which the flames, being deflected by the low roof, must pass. The bottom, or hearth, which is supported, from below, along each side by the inner walls of the flues, and in the middle by a longitudinal wall of brick, is made of brick laid on suitable steel supports. These bricks are covered with a layer of sand and medium coarse gravel. The bottom should be solid and firm, so that it will not be torn up easily by the charging of the plate. The ends of the furnace are provided with narrow, transverse, arched openings, just above the hearth level to permit the charging and drawing of the skelp. Each of these two openings may be closed by an adjustable shield, or, if the furnace is a large one, by a number of smaller lifting doors.

The Bending Furnace Equipment: Located at one end of the bending furnace will be found its charging machine. These machines vary in construction to suit the size of pipe to be welded. For the smaller sizes of pipe, two to four inches in diameter, the strips for which may be charged in piles of thirty to forty pieces, the charging machine may take the form of a stationary table. The piles of skelp are placed on this table, the top of which is on a level slightly higher than the bottom of the furnace, and shoved into the furnace by means of a mechanically propelled pusher. To avoid tearing up the bottom of the furnace, the front end of the bottom piece in each pile projects beyond the others and is bent up like a sled runner. Plate for pipe larger than four inches, and in some mills all plates, is charged in single pieces to lie side by side on the bottom of the furnace. The furnace is, therefore, considerably wider than that for smaller pipe, and the charging machine is mounted on trucks that move on tracks laid across the space in front of the furnace.

Scarfing and Bending Machines: At the opposite end of the bending furnace, the drawing end, is located the scarfing and bending machines. For pipe up to ten inches in size, the plates for which have not been scarfed in the rolling mill, these appliances consist of a set of scarfing rolls mounted on a table that moves transversely before the end of the furnace, and a bending die, which is usually stationary for large pipe but may be mounted on a movable table for small pipe. The scarfing rolls, a three-high stand driven by an electric motor, also mounted on the table to move with the rolls, are placed very close to the end of the furnace, so that, by pushing the heated skelp forward a few feet, it is caught by the rolls and pulled from the furnace. A wide flat groove with bevelled edges cut in the middle roll, or such a groove formed by sleeves that fit over the ends of this roll, produces the scarfing on the edges of the plate. The old style scarfing rolls are two-high. In such a stand the scarfing groove may lie in the top roll only, or it may be formed by cutting a bevelled collar on one end of each roll and placing the rolls in the housings so that these collars are on opposite sides of the plate. By lateral adjustments, these rolls can

be used to scarf plates differing by 15 inches or less in width. The three-high rolls present many advantages over the two-high type, which has, therefore, been practically abandoned by the National Tube Company. The rolls deliver the plate upon the table, at the farther end of which the bending die is located.

The Bending Dies: This die, made of cast iron, is so formed that, with proper manipulation, the drawing of the heated plate or strip through it bends the flat into the form of a split tube with edges overlapping the proper amount for welding. At the entering end of the die the skelp is almost flat, but its edges gradually curve upward as the opposite end is approached, until at the delivery end of the die it has the form of a split cylinder. A kind of mandrel for starting and controlling the bend in the plate is suspended from a frame over the die in such a way that it may be used as a hammer for starting the bend in the plate and for exerting pressure along the longitudinal axis of the plate as it is being drawn through the die. A short pair of tongs, drawn by means of an endless chain, is employed for drawing the plate through the die.

Bending Rolls: The die cannot be used to bend the skelp for pipe larger than sixteen inches, nominal size, and is seldom used on skelp for pipe over twelve inches. Therefore, the skelp for most pipe larger than ten inches and all pipe larger than 16 inches is bent with bending rolls.

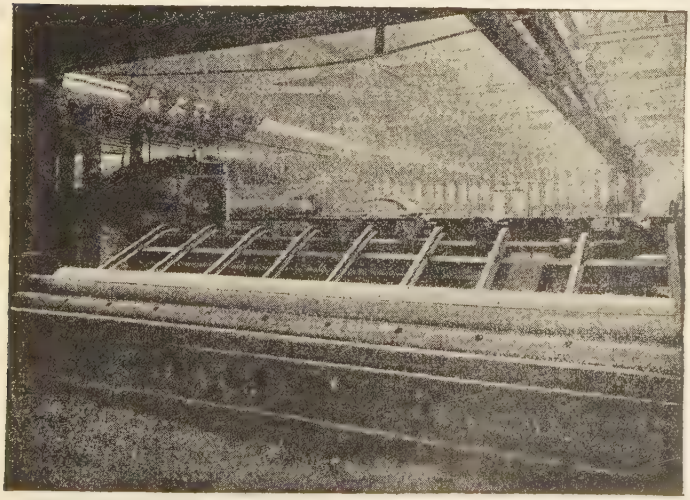


FIG. 287. Bending Rolls, showing a plate bent into cylindrical shape to form large size lap-weld pipe.

These rolls are three in number, and must be slightly longer than the skelp to be bent. Two of these rolls, the bottom rolls, are set in housings with their axes in the same horizontal plane, while the third, one end of which is supported by a swing bearing and the other end by a spherical bearing, is directly above and between these two. All three rolls are geared together and are driven by an electric motor. The rolling surface of the top roll is slightly lower than the rolling surface of the bottom rolls, so that, when a plate is passed laterally into the rolls, it is curved into almost the form of a cylinder. A pressing device located above the rolls is sometimes employed to complete the bending so as to lap the edges at the end of the first turn, after which the rolls are brought into play and the plate is given several turns to make the bending and lap uniform. The skelp is then withdrawn from the rolls by lowering the swing bearing from the forward end of the top roll and drawing the skelp forward, the top roll meanwhile being supported by an over-hanging bearing at the opposite end.

Bending Die for Small Pipe: As pointed out in a previous paragraph, the skelp for small pipe is frequently scarfed in the rolling mill. In pipe mills where this practice is followed, there is no necessity for the scarfing rolls on the small bending furnaces, and in that case the bending die is placed directly before the furnace. It is mounted on one end of a draw-bench. This end of the draw bench is mounted on wheels, while the other end is pivoted, so the die may be moved through an arc before the end of the furnace and be brought thus directly opposite each pile of plates.

The Lap-Weld Furnace is built directly to one side of the bending furnace, and is of the same general design. It must, however, be constructed of much better refractory materials in order to withstand the higher temperatures employed in welding. Except for support walls and outer courses, first quality fire brick is used throughout, but silica brick may be used economically in the bottom and in the roof. The bottoms of these furnaces merit special mention. Since the skelp is in a cylindrical form and the temperature of the furnace must be kept at about 1450° C. (2642° F.), or sixty to a hundred degrees centigrade above the melting point of the scale, special attention must be given to the construction of the bottom to give it a form that will support the bent skelp with the least effort on the part of the workmen and in the best position for heating, which position is with the lap up; and that will permit the bottom of the furnace to be kept free from the liquid scale, which may produce defects in the finished pipe. As a flat bottom will not meet these requirements, the bottom of the lap-weld furnace is made up in the following manner: Beginning with the sides of the floor along the bridge walls in front of the up-and-down take flues, the bottom is built out level for several inches to form a longitudinal shelf or ledge. This distance varies in different furnaces and must be large enough to permit the largest bent skelp the furnace is designed for

to lie on the ledge without touching the bridge wall. From the edge of the ledge on each side of the furnace, the floor slopes downward to a depression in the bottom, known as a gutter. There are usually two gutters to a furnace, placed one on each side of the center line and separated only by a ridge built up of bottom material along the center line. They extend parallel to each other from end to end of the furnace, and are inclined toward the charging end so that the molten scale, or liquor, will flow toward this end. The gutter is made sufficiently wide that a pipe may lie within it without touching the sides of the gutter. In this way the pipe may lie in the gutter with the least possible area of its wall in contact with the refractory materials, and a most efficient drainage for the liquor is provided. The materials used for making up this bottom are sand for the lower layers next to the bricks, coarsely crushed china or crockery, and finely crushed ganister or calcined fire clay. The ends of the furnace are closed with brick walls in which at least six suitably shaped openings for charging, manipulating, and drawing the skelp, and for making up and repairing the bottom are provided. Four of these openings are in the charging end of the furnace; two, one on each side opposite the skelp ledges, are round in shape, and two, opposite the ends of the gutters, are triangular in form. Sometimes two small slag holes, also, are placed at the outer sides of and below the ends of the gutters. The other two large openings are opposite the farther ends of the gutters on the drawing end of the furnace.

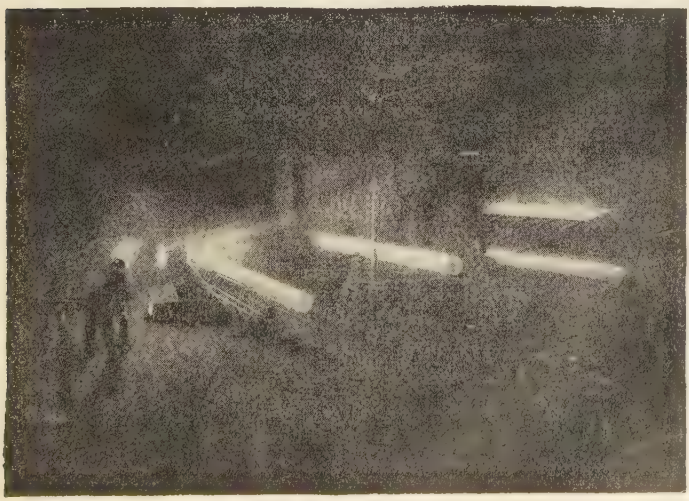


Fig. 288. Charging Skelp into Furnace where They are Reheated for Lap-welding.

The Lap-Weld Furnace Equipment consists of a charging machine, or table for charging the bent skelp; welding rolls, a bar pulling machine, sizing rolls, and cross rolls,—all for welding and forming the pipe; suitable transfer and cooling tables for handling the hot pipe; and a number of small hand tools for manipulating the skelp and repairing the bottom of the furnace. The charging machine may be of the stationary or of the movable type. If of the former type, two are required, one opposite each charging hole. A machine of this type consists merely of a grooved table for supporting the skelp at the proper height and a pushing device, usually a fork propelled by an endless chain, for pushing the skelp into the furnace. In the movable type this table, together with the motor for operating it, is built on trucks mounted on flanged wheels that roll on rails laid before the furnace. Since natural gas is no longer available, the furnace is usually fired with producer gas.

The Welding Appliances: At the drawing end of the furnace are the welding rolls, a two-high stand set as close as may be against the end in order to receive the skelp direct from the gutter. These rolls may be

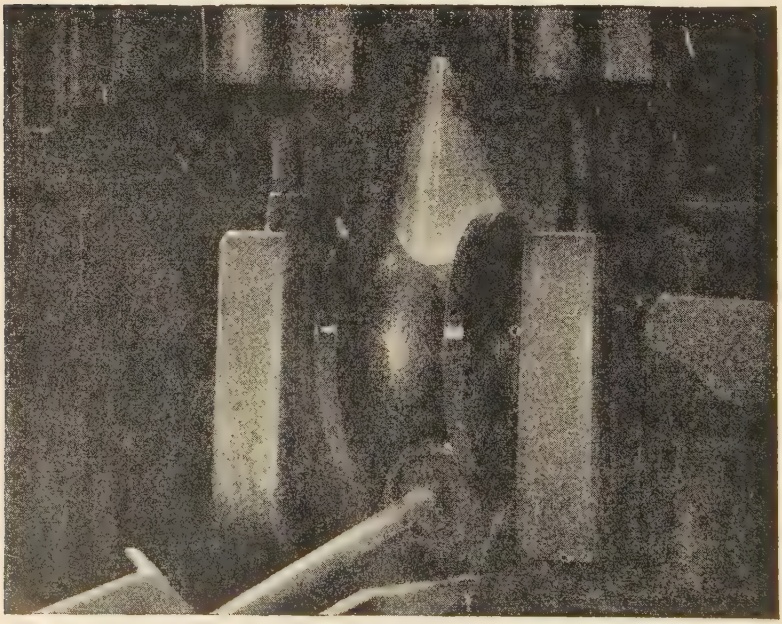


FIG. 289. Lap-welding Rolls, showing Mandrel in position to receive Skelp.

made of either cast iron or steel. They have very short bodies, and contain but a single groove in each. When they are set up in their housings, the grooves form a pass that is practically round, special care being taken in their design to prevent the formation of fins on the skelp as it passes through them for welding. In order to secure the pressing effect of the rolling, essential for good welding, they are of relatively large diameters, thirty to forty inches, according to the size of pipe to be welded. They are provided with bearings, adjusting screws, pinions and connections similar to those on the ordinary rolling mill. They are motor driven, usually with direct current. On the entering side, the rolls are protected by a trumpet guide, and on the delivery side a "trough" made of iron or steel castings is provided for receiving the pipe as it comes from the rolls. In this trough lies the mandrel bar, supported so that one end will extend to the pass in the rolls during the welding process. This end is provided with a collar and a neck upon which the mandrel itself is placed just previous to welding. This mandrel, commonly spoken of as the welding ball, is shaped somewhat like a blunt-nosed rifle bullet or projectile. It is made of cast iron or, preferably, of a special manganese steel. This steel contains manganese, 12 to 14%; nickel, 2.75 to 3.25%; chromium, .90 to 1.10%; and carbon, about 1.25%, and gives from forty to fifty times the service cast iron does. Whether made of this steel or of cast iron, this ball is

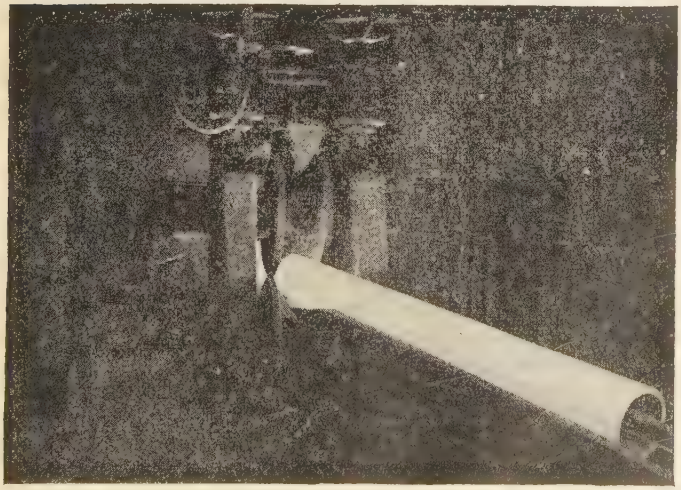


Fig. 290. Showing Pipe passing through Lap-welding Rolls over Mandrel.

cast hollow. A hole in its base along the central axis provides a means of attaching it loosely to the mandrel bar, while other holes may be symmetrically placed on one of the larger circumferences of its nose, if the ball is a large one. At the farther end of the trough, the other end of the mandrel bar is clasped in the bar-pulling machine and is held in place by a stop during the rolling-on of the pipe. The bar pulling machine consists of a two-high stand of rolls provided with grooves for gripping the bar. They are also motor driven. With respect to the construction and arrangement of the welding rolls, there are two types; namely, the stationary and the movable. In the stationary type, two stands of rolls are employed, one in front of each gutter. These two stands are coupled together and driven with one motor. This arrangement necessarily requires two troughs and two sets of pull-off rolls. In the movable type, one stand of rolls, together with its motor and all its other necessary parts, is mounted upon a strong truck so that it can be moved from one gutter to the other.

Special Furnaces: Another arrangement of stationary rolls, in which a single stand is placed at each end of the furnace, is employed on special work, as in the welding of boiler tubes. In order to strengthen the weld as much as possible, these tubes are given two welding passes, or a double run. To lessen the amount of handling necessary on an ordinary welding furnace, save heat, facilitate the welding, and thus increase the output, a furnace specially designed for this work is necessary. A double-run furnace has a welding pit and a set of welding rolls at each end. The bottom is made up in halves, which slope in opposite directions and contain one gutter in each. Since the last end of the skelp to pass through the bending die must be the first to enter the welding rolls, the finishing end of the welding furnace is built in line with the drawing end of the bending furnace. With this arrangement, the hot, bent skelp may be delivered by a transfer table to the first charging hole of the welding furnace and immediately pushed in upon the heating ledge.

The Sizing and the Straightening Rolls are similar to those used in the butt-weld process, but larger and heavier to adapt them to the larger sizes of pipe made by this process. They are located on a line to one side of and parallel to that of the welding and pull-off rolls, so that the pipe may be delivered from the welding trough down a slightly inclined table to a trough directly in front of the sizing rolls, and from the sizing rolls directly into the straightening rolls. Large pipe may require three passes, in the same set of straightening rolls, to straighten it. In the case of "double length pipe" two stands of straightening rolls set in series are provided. The straightening rolls are kept cold by means of water, copiously sprayed upon them. Cuts showing both the sizing and the straightening rolls will be found on the next page. These rolls deliver the pipe to a trough, in the bottom of which is placed a lifting device for transferring the

FIG. 291. Sizing Rolls which give lap-weld pipe correct size.

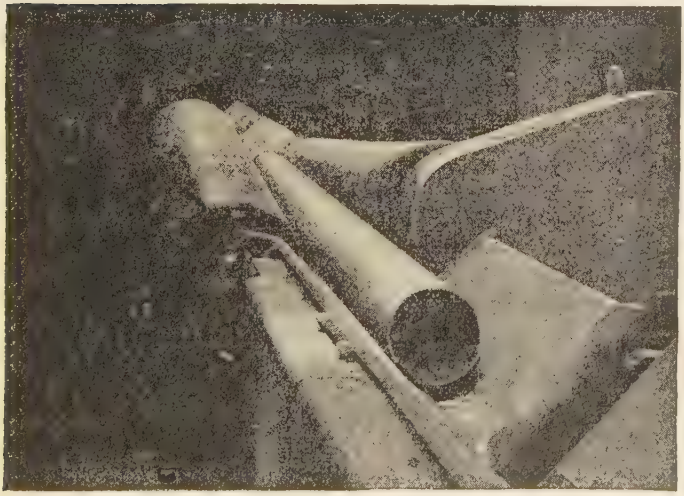


FIG. 292. Cross-rolls which straighten lap-weld pipe and give it a truly cylindrical shape.

pipe to the cooling table built alongside. This table is inclined upward at an angle of about 10°, and is made of rails or beams spaced about two feet apart. Lugs, attached to endless chains that travel over sprocket wheels, are employed to cause the pipe to roll up this incline, so that the cooling will be uniform. For large pipe, the table may be provided with saws near the cold end for cutting off the crop ends, and in the case of double furnaces, for cutting the pipe in the middle. Pipe five inches and over in size is sometimes sawed, but, in general, pipe may be either sawed or cut in lathes, which are conveniently located at the cold end of the cooling table.

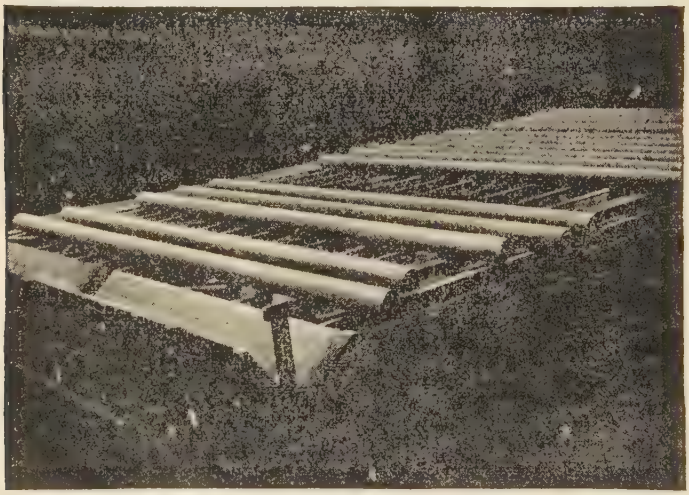


Fig. 293. Cooling Table for Lap-weld Pipe.

Operation of the Bending Furnaces: The charging of the skelp into the bending furnace is in the hands of a workman known as the "plate charger." He also determines when the plate, or skelp, has reached the proper temperature for drawing, and, if the scarfing has not already been done, pushes it into the scarfing rolls. Although the temperature of the plate is low, about 800° C., it should be uniformly heated to secure good scarfing and bending. This result is obtained by proper regulation of the gas supply, and by regularly reversing the flame in the furnace. Usually, these reversals are made at intervals of 30 minutes. The plate expands about .01 inch per inch in the bending furnace. Bending, the next step, is also an operation that requires considerable care, as improper bending may result in many defects in the finished pipe. Care is required to see that the edges of the bend have the proper amount of lap, and the seam is straight without any spiral curve to it whatever. The ends of the larger

sizes of pipe should be tied after the bending, so that the edges will not sag or the bend collapse in the welding furnace. On pipe from eight to twenty inches in size, this tying is done by reversing the lap at each end of the bend with a bar and pounding down the corners with a hammer. The bend for pipe more than twenty inches in size is tied by electrically spot welding the overlapping corners of the skelp. The bending is in charge of a workman known as the plate bender, who requires one assistant, called a tong runner, if the bending is done with a die, or two assistants, if bending rolls are used. The bent skelp, which is still at a dull red heat, is at once transferred to and charged into the welding furnace. Many different types of apparatus are employed to effect this transfer, but the overhead crane with hanging hooks or fingers is most flexible and the device most often employed for the larger sizes of pipe. If a die is employed for bending the skelp, the first end through the die is deformed by the tongs and not well lapped. The last end through the die, therefore, must be the end foremost when the skelp is charged into the welding furnace.

Operation of the Welding Furnace: The operation of the welding furnace is directly in the hands of the welder, or his first assistant, who is sometimes called a speller. His other assistants are a charger and two or more turn-downs. The latter attend to rolling the skelp from the shelves or ledges, to the gutters. All these men are stationed and work in a space known as the welding pit, at the charging end of the furnace. It is the welder's duty to see that the skelp is properly heated for welding and that the bottom of the furnace is kept in good condition. Proper heating requires that the skelp be uniformly heated and neither over-heated nor under-heated. Uniform heating is secured by having the furnace sufficiently hot to begin with, by properly regulating the gas and air for combustion, by reversing the flame in the furnace at proper intervals, and then observing a fixed order for charging and drawing. The reversals of the flame are usually made every thirty minutes. More frequent reversals may increase the temperature and less frequent may result in too low a temperature or non-uniformity in the furnace temperature. For the best results the temperature of the furnace is maintained at almost 1500° C. (2732° F.). The temperature for welding, always determined by the eye, is reached at the point where the scale begins to melt, or, in mill terms, where the liquor begins to flow. This temperature is in the neighborhood of 1350° C. (2462° F.) or slightly higher. Since no flux can be used to lower the melting point of the scale, heating to a lower temperature results in a poor weld, or no weld at all. When it is considered that the point at which a .10-per cent. carbon steel begins to melt is about 1455° C. (2650° F.), the range between under-heating and over-heating is seen to be very narrow.

The Order of Charging and Drawing is also an important factor in heating, and, besides, it may affect the output of the furnace. The details of operating any furnace may vary a great deal, but the operation

of a single-run furnace may be described about as follows: In starting welding operations in such a furnace, a piece of hot skelp from the bending furnace is charged upon, say number one ledge, where it is allowed to remain until it reaches what appears as a dark red heat in the light of the furnace, when a second piece from the bending furnace is charged on number two ledge. The first skelp charged is then turned down into number one gutter, not forgetting that the skelp must always lie in the gutter with the lap up. Then a third piece is charged on number one ledge, the second piece is turned down into number two gutter, and a fourth piece is charged on number two ledge. When the first piece in number one gutter has reached the proper temperature for welding, which point is personally determined by the welder, it is pushed forward about four feet through the guide directly into the welding rolls. The third piece is then turned down into number one gutter, and a fifth piece is charged on number one ledge. The second piece charged is then drawn from number two gutter, the fourth piece turned into number two gutter, and a sixth piece charged on number two ledge. This order is then repeated, the skelp being charged and drawn from the two sides of the furnace alternately.

Repairs to Bottom: During these operations the bottom of the furnace must be looked after and kept in good repair. The gutters require special attention to see that they are kept in proper shape, so that they will drain the liquid scale away from the skelp and permit the latter to leave the gutter with a surface free from splotches of scale or other foreign bodies. Adhering bodies of this kind produce defects in the finished pipe, the more common of which are those known as liquor marks, large scab- or pit-like depressions occurring along a longitudinal line on the outer surface of the pipe.

Operation of the Welding Rolls: Before the skelp is pushed out of the gutter, the welding ball is attached to the end of the mandrel bar and then inserted by moving the bar forward, between the welding rolls, so that its nose projects beyond the contact points of the rolls, thus leaving the cylindrical portion in a position to receive the pressure for welding. The bar is then locked in position by the stop. When the skelp, with the lap up, is pushed from the gutter, it slips over the nose of the mandrel and is grasped by the revolving rolls, which continue to pull it forward rapidly over the welding ball. Great pressure is thus brought to bear on the lapped edges of the skelp, the liquid scale is forced from between them, their surfaces are brought into that intimate contact necessary for welding, and the lap itself is rolled down to a thickness corresponding to the rest of the circumference. Since the peripheral, or delivery, speed of the rolls is about 600 feet per minute, these effects are produced on a 20-foot length of pipe in about two seconds of time. The bar-pulling machine is now brought into play, the welding bar is withdrawn from within the pipe, which now lies in the trough, and the welded pipe is moved down an inclined table before the sizing rolls. These operations are in the hands of two

workmen known as the baller, or ball setter, and the puller, or bar puller. An assistant picks up the ball, which drops from the bar when the latter is withdrawn, plunges it into a tank of water, and, when it is cold, cleans its surface of the welding scale that adheres to it. The removal of this scale from the inside of the pipe by the ball, makes the use of scaling rolls, such as are used on butt-welding pipe, unnecessary. A workman known as the "taker-off" is stationed at the table in front of the sizing rolls. He inspects the pipe, giving special attention to the weld. If the pipe contains defects that he can discover, he either sends it to a scrap floor, or, if the defect is in the weld, to the welding pit to be rerun, that is, recharged and rewelded. A good welder, working, with a good crew and good fuel, on the small sizes (2 in. to 4 in.) of standard pipe, will produce pipe at the rate of about two twenty-foot lengths per minute, nearly all of which will be satisfactorily welded on the first run.

Welding Special Tubes: In the case of boiler tubes and other special work that is given a double running, the tube from the bending furnace is pushed in upon the heating ledge of the welding furnace, turned to secure uniform heating, and finally rolled into the gutter with the lap up. Thence, as soon as the welding temperature has been attained, it is pushed into the first welding rolls for the first run. Then after the bar has been pulled, the tube is again charged for the second run on the opposite side of the furnace. Here, it is turned into the gutter with the seam up, the welding temperature is restored, and the tube is pushed into the second welding rolls, thus issuing from the same end of the furnace into which it was first charged. It is then transferred over a take-off table to the sizing and cross rolls, through which it passes in succession.

Operation of Sizing and Cross Rolls: After passing the inspection by the "taker-off," the pipe or tube passes directly into the sizing rolls, where it is elongated slightly and compressed to a uniform outside diameter. Unless this diameter is constant and all the diameters are uniform, difficulty is encountered in threading the pipe, and the couplings will not fit properly. Considering that proper allowance must be made for the contraction of the pipe in cooling, the cutting of the grooves in these rolls and their adjustment requires considerable skill and experience. If these rolls are allowed to get only slightly out of adjustment they will bend, twist or otherwise deform the pipe. They, therefore, require constant attention. Their adjustment is in the hands of a special workman, known as the roll setter, who also attends to the adjusting of the welding and straightening rolls. The latter rolls receive the pipe or tube as soon as it has cleared the sizing rolls, and by the reeling action already described, deliver it, properly straightened, upon the trough before the cooling bed.

Finishing Operations: Up to this point the manufacturing processes described in the preceding paragraphs are basic, and, except as to details, are common to all lap-welded tubular products; but the finishing operations

are subject to considerable variation according to the class or kind of product being made. Owing to the fact that these products are numerous, it is not advisable to trace each product through its finishing processes separately. Therefore, in order to indicate how the pipe is handled and show some of the chief features of finishing, we shall first describe briefly the finishing operations on Standard pipe and lap-welded boiler tubes, and then some of the more important supplementary operations to produce the special types of welded steel tubular products.

Finishing Standard Pipe: Upon arriving at the cooling bed the pipe is still red hot. In order to make the cooling as uniform as possible, the pipe is slowly rolled along the cooling bed by means of lugs attached to endless chains. The length of the cooling bed and the speed of travel are such that the pipe is usually cooled by the air enough to handle by the time it reaches the farther end. Large pipe may be sprayed with water after it has cooled in air to a dark red or black color. At the cold end of the cooling bed the pipe is inspected for visible defects, and occasionally a pipe may be weighed, as a check on the adjustment of the welding and sizing rolls. The pipes are next delivered to the cutting-off machines where the rough ends left from the welding operation are cut off. This cutting may be done in lathes, or by saws. The pipe is now delivered to inspection tables, where it is closely inspected for surface defects and sorted about as described for butt-weld pipe, the defective pipe being treated as required to eliminate the defects. The pipe that passes this inspection is delivered to the threading machines which cut off and true up the ends, ream the edges inside and out and cut on the threads. Both ends of the pipe are threaded in succession in accordance with the American (Brigg's)

Fig. 294. Pipe Threading Machine.

Standard, the machines in some cases automatically stopping the process when the threads have been cut back the required distance.

Inspectingand Testing Standard Pipe: From the threading machines the pipe passes over a table to the hydrostatic testing machine, and on the way the threads are doped, the couplings are put on, the pipe is given a final inspection for surface defects, and if not otherwise specified, it is oiled. The couplings are tightened by machine, the operator taking care to see that the coupling is not forced beyond the perfect threads. On large sizes and all special pipe, the inspection not only covers surface defects, but also the threading, including the taper. For this purpose a standard gage-coupling is used. The pipe is next subjected to the hydrostatic test in a machine like that described for testing butt-weld pipe. As to the pressures employed, these vary, for Standard lap-weld pipe, from 600 to 1000 lbs. per sq. in., according to size. It should be noted, however, that for lap-weld pipe other than Standard, the test pressures vary from 450 to 3000 lbs. per sq. in., according to the size and the service for which it is intended. After each pipe has been tested, it is stenciled and prepared for shipment.

Finishing Boiler Tubes: From the trough leading from the straightening machine, each tube is lifted mechanically and deposited upon the lower end of an inclined cooling bed, upon which the tube is slowly rolled by means of endless chains. This table is made so long that the tube is cool

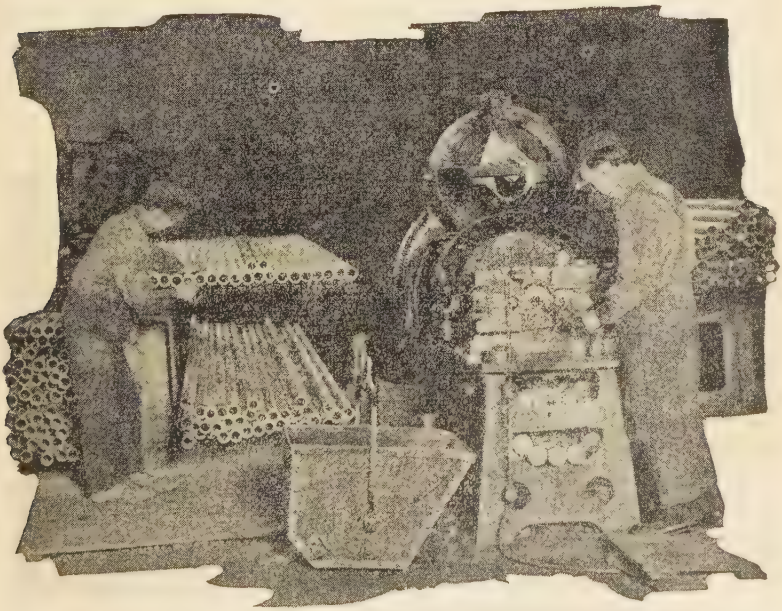


Fig. 295. Inspecting and Cutting Off Rough Ends of Boiler Tubes.

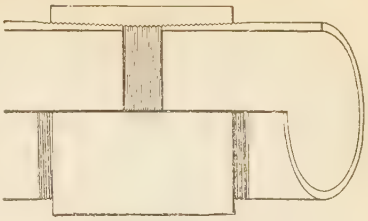
enough to handle by hand when it has reached the farther end. Here the tube is given a straightening operation by hand and carefully inspected by the men operating the lathes. The tube is then placed in a lathe and the crop ends cut off, leaving the tube of the length desired. Both ends cut off are tested for quality of the weld and material. This test, in the case of standard boiler tubes, is made by inserting the crop end in the press in such a manner as to flatten out a section with the weld near the point of maximum bend. In order for the tube to pass this test, the weld must not show any signs of opening. The tube is then subjected to a rigid inspection covering length, straightness, rotundity, gage, weight, and all surface defects. All boiler tubes under five inches in diameter are subjected to a hydrostatic test, in which is applied an internal pressure of 1000 lbs. per square inch. In tubes five inches or over in diameter, this pressure is varied from 500 lbs. to 800 lbs. per square inch, so that the fibre stress does not exceed 16,000 lbs. per square inch. All tests are made in accordance with the standard specifications, such as those of the American Society for Testing Materials, and the American Society of Mechanical Engineers.

Special Pipe: The finishing operations on special pipe vary with different classes of products and the manner in which the pipe is to be connected. In general, pipe connections may be of five kinds or classes, namely, screwed, flanged, leaded, riveted and welded.

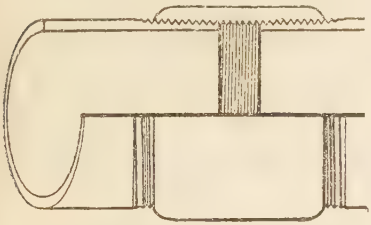
Screwed Joints: The different pieces of pipe may be screwed together in several ways, the most common of which consists of threading the ends of the pipe externally and connecting these ends by means of couplings threaded inside, as in the case of standard pipe. This method is generally applicable to all sizes up to 15 inches. Pipes may also be screwed together without a coupling. Thus, as is sometimes done with oil well casing, one end of the pipe may be expanded, so that, when it is threaded inside it will fit over the unexpanded end, which is threaded as for couplings, thus forming an inserted joint. Instead of expanding, one end may be swaged down so as to be inserted in the adjoining unexpanded end. Pipe, which has a wall sufficiently thick to permit it, may be connected with the flush joint, which is made by machining and threading one end externally to fit into the adjoining end also machined or chamfered and threaded internally. The accompanying cuts (Fig. 296) illustrate the different styles of screw joints.

Upsetting: As the cutting of the threads for the couplings weakens the pipe somewhat at that joint, the ends of pipe to be used for certain purposes, such as oil well drilling, may be upset before cutting on the threads. To accomplish this upsetting, the end of the pipe is heated to a full forging temperature, then inserted endwise between two semi-circular dies of the upsetting machine. These dies clamp the pipe from the outside, while a mandrel carrying a collar of the exact size of the outside diameter of the upset end, is inserted into the pipe. As the mandrel advances, the collar comes in contact with the end of the pipe and pushes the hot metal back

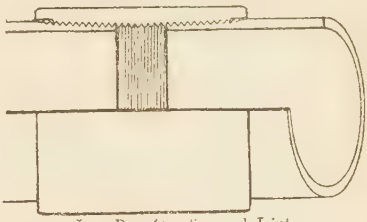
to fill the ring-like space between the mandrel and the die. By changing the design of the dies, the upsetting may be controlled to throw the extra thickness either on the inside or the outside of the pipe. Following these forging operations the upset ends of the pipe are normalized by heating to about 900° C. and cooling in air.



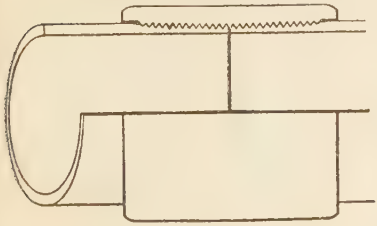
English Steam and Gas Tube



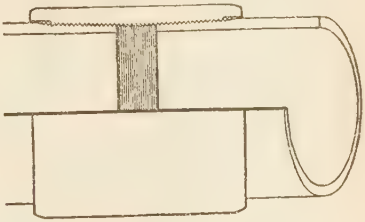
Standard Pipe Coupling and Joint



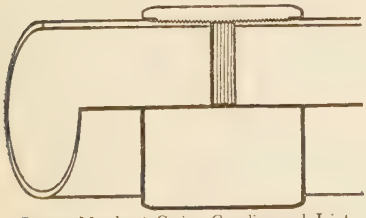
Line Pipe Coupling and Joint



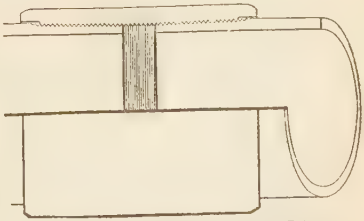
Drive Pipe Coupling and Joint



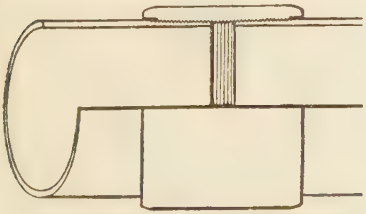
Oil Well Tubing Coupling and Joint



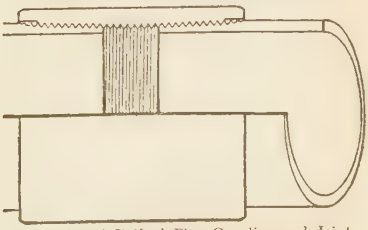
Boston Merchant Casing Coupling and Joint



South Penn Casing Coupling and Joint



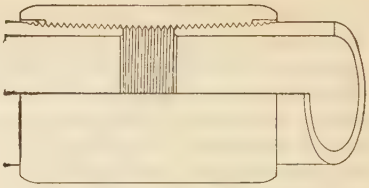
Boston Oil Well Casing Coupling and Joint



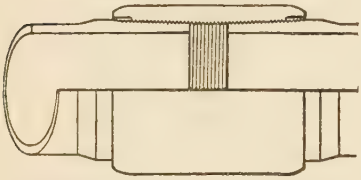
Reamed and Drifted Pipe Coupling and Joint

FIG 296. Showing Different Varieties of Pipe Screw Joints.

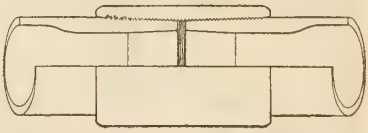
Diamond BX Casing Coupling and Joint



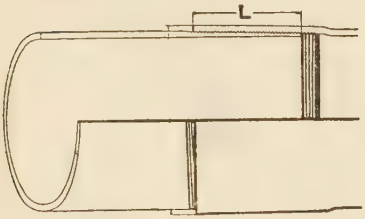
Rotary Drill Pipe Coupling and Joint



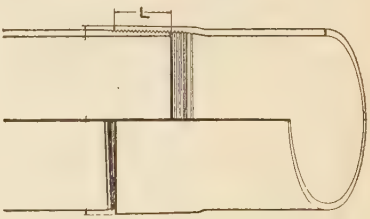
External Upset Tubing Coupling and Joint



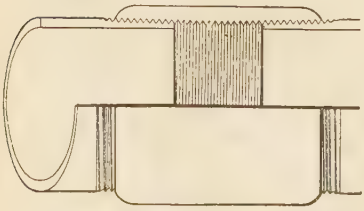
Interior Upset Drill Pipe Coupling and Joint



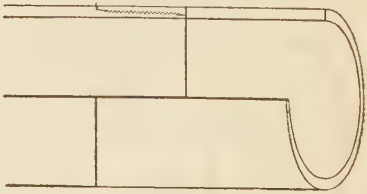
Export Std. Inserted Joint Casing



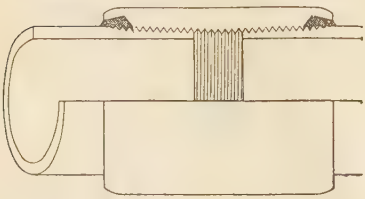
Boston Inserted Joint Casing



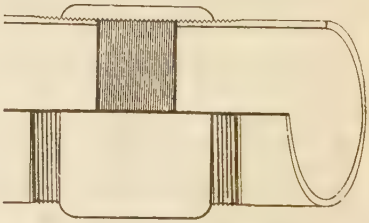
Ammonia Pipe Coupling and Joint



Flush Joint Tubing



Air Line Pipe Coupling and Joint



Dry Kiln Pipe Coupling and Joint

FIG. 296. Showing Different Varieties of Pipe Screw Joints.—Contd.

Leaded, or Bell and Spigot, Joints: For water and gas supply mains and other hydraulic lines that are not to be subjected to high internal pressures, leaded joints are generally employed. Formerly the leaded joints were of several different designs or kinds, but the kind most generally used at present is known as the bell and spigot joint. In this joint one end of the pipe, the bell end, is expanded to permit the insertion of the unexpanded end of the preceding length or section, which end is known as the spigot end. The small part of the bell fits rather snugly over the spigot end of the pipe, while the large part provides for an annular space between the bell and spigot. In laying this pipe, for water lines, the base of this space, after forcing the bell over the spigot, is calked with hemp and the remainder of the space is then filled with lead. The National Tube Company employs an improved design of this type of joint, which is known as the Matheson joint. In this joint an annular groove is turned on the spigot, which, with the peculiar design of the bell, provides for the firm retention of the lead and tends to prevent the spigot from pulling out of the bell after the pipe is assembled in the line. To provide greater rigidity at the joint, the bell is completely covered outside by a reinforcing ring or jacket. The maximum pressures to which this joint may be safely subjected depends upon the service and the diameter and thickness of the pipe, but, in general, the regular joint can be used for working pressures as high as 150 pounds (347-foot head), and it has often been used for pressures up to 200 pounds (462-foot head). By reinforcing the joint with flanges and bolts, it can, with proper care in laying, be made suitable for pressures up to 350 pounds (807-foot head).

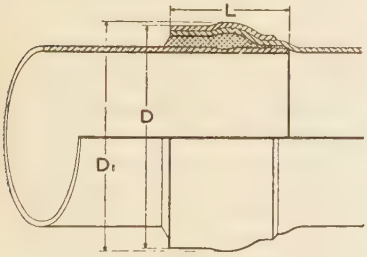


FIG. 297. Matheson Joint

Flanged Joints are used on pipe intended for high pressure lines and for other special purposes. A particular advantage in this type of connection is the ease and readiness with which sections of a line may be removed and replaced. These joints are usually applied to pipe larger than three inches, but are sometimes used on pipe as small as two inches. They are made by attaching flanges, provided with suitable bolt holes, to the adjoining ends of the pipe, facing and butting those ends together, usually with a gasket between, and securing them with bolts. The flanges may be attached to the ends of the pipe in a number of ways. For low pressure lines, and for high pressure lines in sizes up to eight inches, they are frequently screwed on, the pipe ends and the flanges being threaded as for ordinary couplings. A method that is often preferred for sizes of pipe larger than six inches, consists of shrinking the flange on the end of pipe and then peening over, or otherwise expanding, the end into a recess

provided in the face of the flange. For high pressure work the joints known as the welded flange joint and the Van Stone joint are best. In the first, the flange is welded to the end of the pipe, thus becoming a part of the pipe itself. In practice this joint is generally reliable, though it is evident that its success depends upon the manner of making the weld and the care with which it is made. In the Van Stone, or loose flange joint, the flange, which is bored slightly larger than the outside diameter of the pipe, is slipped over the end of the pipe, which is then heated, upset and flared hot at right angles to the pipe, itself. To insure a tight joint the flared ends of the different sections of the pipe are faced, so that when the pipe is in position the adjacent ends will fit nicely against the gasket. Since the flanges are loose, they serve simply to draw and hold the flared ends of the abutting sections together against the gasket. This construction provides a perfect joint under various conditions and adapts it to practically all kinds of service. In the case of lap-weld pipe, flanged joints, as a rule, are not formed at the pipe works, these joints being manufactured by the fabricators.

Riveted Joints are of two kinds, known as butted-and-strapped and bump joints. The first is made by butting the two pipe ends together, covering the joint with a steel sleeve, or strap, either externally or internally, and then riveting and calking the ends of the two pieces of pipe to this sleeve. For the straight bump joint, one end of the pipe is expanded for a short distance to slip over the other, when the two ends are riveted together and calked. For mechanical reasons, riveted joints are applicable only to large sized pipe, say 26 inches and over. Therefore, these joints are of only minor importance in connection with lap-weld pipe. In the utilization of large pipe, however, such as that produced by the hammer-weld process to be described next, bump joints rank among the most popular joints.

The Welded Joint presents many advantages over other joints for many kinds of work. Among these advantages may be mentioned greater permanence, efficiency and strength of joint, and less tendency to leakage, which factors make for a low cost of maintenance. Again, the elimination of all fittings and couplings, a saving of time or labor or both to lay the pipe, and its greater flexibility after joining result in lowering the cost of installations. The method pursued in making these joints is that of autogenous welding, and of the three ways of making the autogenous weld, the blow-pipe, or oxy-acetylene, method is the one most generally used for coupling pipe. With it joints practically as strong as the remainder of the pipe can be made.

Testing and Inspecting Special Pipe: After the necessary work has been done on the ends of the pipe to prepare it for the kind of coupling desired, it is oiled, unless oiling would be objectional, then put in the testing machine and subjected to the internal hydrostatic pressure, which

varies with the size and kind of the pipe and the use to which it is to be put. The perfectness of the weld is determined on the crop ends as the pipe is being cut. Each of the two crop ends from each piece is bent nearly flat in a press in such a manner that the seam will come near the bend. In order to pass this inspection the seam must not open or give way. This test is not possible on butt-welded pipe. A much greater surface and more pressure for welding are available in the lap-welding than in the butt-welding process, and the weld is, therefore, much stronger. The pipe is then weighed, tallied, provided with thread protectors, if needed, and made ready for shipment.

Protective Coatings: In order to protect pipe from corrosion, it may be coated or covered with a number of different substances or mixtures. The substances most commonly used are zinc, bituminous mixtures, and paint. The best coating to use in any particular case depends largely upon surrounding conditions, but ordinarily the zinc or bituminous coatings will afford the greatest protection.

Zinc Coating or galvanizing is widely used, especially on the smaller sizes of pipe. For applying the zinc the hot dip process of galvanizing is used. The finished pipe is first thoroughly cleaned from scale by pickling it in warm dilute sulphuric acid. It is then washed free from adhering acid by dipping it in a bath of fresh clean water, and immersing it in an alkaline or neutral bath for a short period of time. The pipe is then quickly dried, and immersed in a pot of molten zinc covered with ammonium chloride, to protect the zinc and act as a flux. When the pipe has been immersed a sufficient length of time to permit its temperature to reach that of the

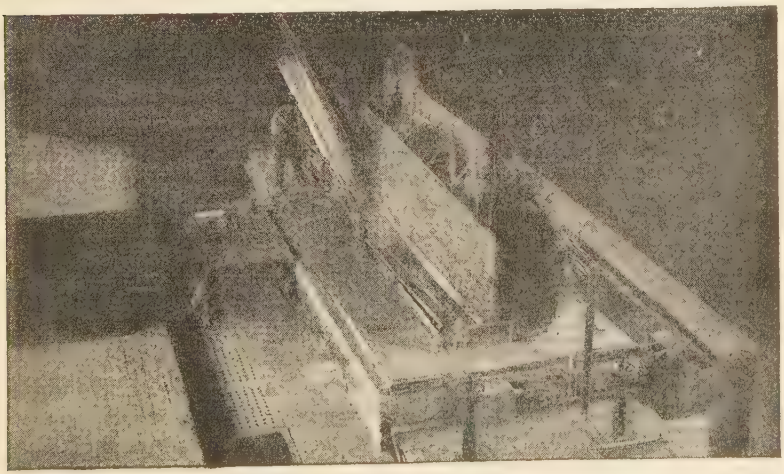


FIG. 298. Removing galvanized pipe from bath of molten zinc.

molten zinc, it is withdrawn, being supported in an inclined position to permit the excess zinc to drain off from both the inside and the outside of the pipe.

Value of Zinc Coating for Pipe: Though zinc has a high solution tension, and the coating is readily soluble in dilute acids, strong alkalies, and some mineral salt solutions, galvanizing affords good protection against ordinary atmospheric corrosion, because the zinc, on exposure to the air, at first reacts with oxygen to form zinc oxide. This reaction only progresses to a limited extent, however, for the oxide remains as a thin film on the surface of the coating and protects the zinc from further oxidation. Besides, since this oxide is insoluble in water and the film adheres rather tenaciously to the zinc, it protects the underlying zinc coat against all ordinary types of weathering. And so long as the zinc coat remains intact, the steel, or iron, beneath is secure from corrosive action, for the coat is impervious to moisture in any form. The zinc will afford some protection to the iron even if the coat is broken, as by bending or abrasion, because, being electro-positive, or anodic, to the iron, it is dissolved instead of the latter as long as any zinc remains closely adjacent to the exposed iron. In the case of underground piping, where the pipe is in direct contact with the earth, galvanizing is not generally suitable as a protective coating, because it may be quickly destroyed by certain acids in the soil.

Bituminous Coating: There are several different bituminous mixtures that have been used for coating pipe. Some of these are composed largely of refined coal tar pitch, but the best are made from certain species of asphalt which are capable of giving an elastic rubber-like coating with a black, smooth, glossy finish that will not chip off from blows or friction when cold nor soften unduly when exposed to the heat of the sun. In applying the coating, the pipe is cleaned of all loose scale, dirt, rust, etc., then dried and dipped into a bath of the coating mixture kept at a temperature above 100° C. (212° F.). After the pipe has attained the temperature of the bath, it is with-drawn at an angle, or vertically, to allow the excess to drain off before it has time to harden. The coating may be dried in air, but is usually baked on to form an enamel-like surface. For some classes of work, this coating is followed by a second in which the pipe is wrapped with a strip of fabric saturated with the same mixture used in dipping, in which case the fabric is preferably dusted with cement before the coating compound has dried. Another advantage of such coatings is that they may be applied in the field, thus avoiding injury to the coat in transporting and handling the pipe.

Pipe Couplings: Pipe fittings, in general, are made of three kinds of material. Such fittings as elbows, tees and unions are made of cast iron, sometimes rendered malleable, or of cast steel, while spigots, cocks, valves, and the like are usually made of brass. With the exception of a limited number of fittings, such as pipe flanges, that may be forged of steel,

and of pipe joints, of which there are about twenty different types, some made of cast iron and some of steel, only the couplings are left to the wrought iron and steel industries. The term coupling is occasionally used to refer to any jointing device, but as used here it is a threaded sleeve for connecting two pipes end to end. Couplings are sometimes spoken of as sockets. Each coupling must be threaded inside to suit the exterior threads on the ends of the pipes to be joined.

Materials for Couplings: Originally wrought pipe couplings, like the pipe itself, were made of wrought iron. Since, in screwing different sections of pipe together, galling is more liable to occur when pipe and couplings are made of the same metal than when they are made of different materials, the use of wrought iron for couplings was continued for some time after the introduction of steel pipe. Then, in order to increase the strength and stiffness without increasing the weight, the "half and half" coupling was evolved by faggotting wrought iron bars with steel bars, both of the same dimensions. When this faggot was heated to a welding temperature and rolled, the bars were welded together, forming a strip or plate with wrought iron on one side and steel on the other. These strips or plates, the width of which corresponded to the length of the coupling to be made, were cut into lengths corresponding to the circumference. These pieces were bent to form split cylinders with over-lapping edges, in which the wrought iron side of the pieces formed the inside of the cylinder. These bends were then heated to a welding temperature and welded to form the coupling blanks, which were then sized, that is, made perfectly round, in a press, then machined and threaded to the exact forms desired. While these half-and-half couplings were stronger than those made only of wrought iron, they were inferior to what could be expected of a coupling made wholly of steel. But the advantages promised by the all-steel coupling could not be utilized on account of the danger of galling. In 1920, however, the National Tube Company succeeded in over-coming this draw-back by electrolytically depositing a thin even coat of zinc upon the inside surface of the coupling after the threads had been cut. By this means the danger of galling exhibited by steel against steel has been entirely overcome, and the half-and-half coupling is rapidly being replaced by the all-steel coupling.

Methods of Making All-Steel Couplings: All steel couplings fall into two classes, namely, welded couplings and seamless couplings. Welded couplings may be made by the general method outlined in the preceding paragraph for half-and-half couplings. Some have also been made by cutting a lap-weld tube of the proper gage and diameter into lengths corresponding to the lengths of the couplings, then sizing and threading these blanks as desired. To realize all the advantages possible in the all-steel couplings, however, the coupling must be made seamless. Seamless couplings may be made in several different ways, but no one method is well

adapted to all sizes of couplings. In one of these methods, the center of a cold drawn round steel bar is bored out on a specially designed machine, for a distance a little greater than the length of the coupling, and the resulting cylinder is cut off. The operation is then repeated until the whole bar is cut up into blanks, which, after threading, are ready for service. Couplings for pipe from $\frac{1}{8}$ inch to $\frac{3}{4}$ inch in size are regularly made in this way. Other methods of making seamless couplings, which are applicable to the larger sizes, involve cupping a plate or piercing and rolling a billet as for seamless tube, the manufacture of which is described in a succeeding section. The tube thus formed is made perfectly round by machining, or other convenient and suitable means, and is then cut into lengths corresponding to the length of the coupling for which it is designed.

Finishing Steel Couplings: After the steel blanks have been formed, they are taken to the machine shop, where the larger ones are first given a final sizing operation on a press. The blanks are now placed in machines which true up the ends, and, if desired, recess the ends internally in the same operation. The advantage of recessing, in protecting the first threads of the couplings from injury until they are put in service, is obvious. Steam pipe and English couplings are not recessed. The couplings are now threaded and tapered, either in one or two operations. Much importance is attached to this part of the work, and great care is taken to see that all threads are properly cut. All couplings are passed upon by the inspection department, which selects at random and at intervals as frequent as may seem necessary a specimen coupling from each machine. The threading in each specimen is carefully gaged and inspected. If faults appear, immediate steps are taken to correct them. The couplings are next taken to the galvanizing department, where they are first washed with a soda solution to remove the oil adhering from the threading operation. The couplings, thoroughly cleaned on the inside, are now placed, several at a time, in a specially constructed plating tank filled with a solution of zinc sulphate. In this tank the couplings are supported so that they collectively form the cathode while large zinc poles project into the couplings and form the anode. Upon the passage of a direct current through the apparatus, the zinc is deposited upon the inside of the coupling as a firmly adhering coat, the thickness of which depends upon the current density and the time. Since the coat will not adhere firmly to the iron if the current density is too great, this factor is limited and fixed to give a tight coat and the thickness is controlled by the time. Usually more than an hour is required to build up a coating of the desired thickness. As an additional safeguard against galling, also to facilitate the tightening up of the couplings and pipe and prevent rusting of the threads in service, a special thread dope composed of zinc dust and non-drying and lubricating greases has been prepared for use with couplings.

SECTION IV.

THE HAMMER-WELDING PROCESS.

General Remarks: The tendency of the bent skelp to collapse in the welding furnace makes it very difficult, and practically impossible in the case of light skelp, to weld pipe larger than 30 inches by the ordinary lap-welding process. Of course, by proportionately increasing the thickness of the plate, it may be possible to lap-weld, with rolls, pipe even somewhat larger than 30 inches, but the extreme massiveness of the furnace and welding machinery required, combined with other conditions, add so much to the cost of production as to render this method economically impracticable. For lap-welding pipe larger than thirty inches, therefore, the hammer-welding, also known as the horn-welding, process is employed. While twenty-inch pipe is about the smallest to which it is practicable to apply this method of welding, there is practically no maximum limit to the size of the pipe that it is possible to make by it. However, the output from any given plant must fall within a certain range, the limits of which are fixed by the equipment. Of course, the logical way is to decide upon a desirable range for the plant and provide equipment to suit, but owing to progress this cannot be done. What appears to be ample today may fall far short of requirements a few years hence. Few people in 1900, for example, could foresee the time when the demand for steel pipe up to eight feet in diameter would justify the great expense of equipping a plant to make it. Yet such plants are now in operation. Because it represents one of the most recent installations, the Christy Park Plant of the National Tube Company is selected as an example of such a plant. This shop is equipped to make hammer-welded pipe from 20 inches to 96 inches in diameter and in lengths up to 30 feet, though by a separate operation, whereby shorter lengths are welded together end to end, longer lengths can be produced. However, the longest length that can be tested is 40 feet.

Skelp for Hammer-Welded Pipe is rolled on sheared plate mills. The rolling practice for this material need not vary from the ordinary, but accuracy is required in shearing. The need for this closer shearing is due to the fact that in order to facilitate the joining of the different pieces of pipe in the line, the diameters must be very nearly uniform. The size of hammer-weld pipe that can be made from a single plate is, of course, limited by the maximum size of plate the plate mills are able to roll. Pipe that would require a plate larger than the plate mills can furnish is fabricated from two or more plates. This fabrication can be accomplished by welding two or more plates together longitudinally, the finished pipe thus having two or more longitudinal welds, or by bending the plates length-

wise and welding two or more of the resulting pieces of pipe together, forming girth seams, or circumferential welds. The steps in the process of making these plates into pipes are bending, welding, annealing, straightening, cutting, and testing, to which may be added, when occasion demands, plate scarfing, end-welding, end-forming, and sizing operations. While lacking in details, the following brief descriptions will serve to impart an idea as to the manner of carrying out these processes at Christy Park, and as to the equipment required to do the work.

Scarfing the Plates: For pipe of certain diameters and wall-thicknesses, the plate is scarfed and bent hot. For this purpose a heating furnace and a stand of scarfing rolls are provided. The furnace is constructed, and its accessories are arranged, along lines similar to the bending furnaces used in the ordinary lap-weld process. A movable charging table is placed at one end, while the scarfing rolls are located at the other. These rolls are electrically driven and are of the three-high type, with the scarfing groove on the middle roll. This roll, the diameter of which is about ten inches and less than half that of the other two rolls, is a built-up roll, that is, the collars forming the scarfing groove are made in the form of sleeves that slip over the ends of the roll. Thus, by changing these collars for different gages, or by merely adjusting them on the roll for plates of the same gage, the one set of rolls is adapted to scarfing all widths of plates up to the maximum the mill is designed to roll. When the plate has reached a temperature corresponding to a dull red in indirect sunlight, it is pushed forward out of the furnace directly into the scarfing groove of the mill, which lies between the bottom and middle rolls. The top roll, therefore, acts merely as a reinforcing roll to the middle one. These rolls draw the plate forward and deliver it, with its edges properly scarfed, upon a stationary receiving table, from which it is passed laterally a distance of about thirty feet to the bending rolls. For most pipe, however, it is not necessary to scarf the plates, in which case the plates, after careful inspection, are bent and lapped cold.

The Bending Machine: The bending of the plates is done on machines similar in construction to the roll bending machines used for bending the larger sizes of ordinary lap-welded pipe. These machines, however, are constructed to give a more accurate bend than the ordinary machine, and can be used for straightening and truing up the pipe after welding. Each consists of four rolls, which must correspond in length to the maximum lengths of pipe to be made. These four rolls are arranged in sets of two in two planes at right angles to each other, one vertical, the other horizontal. For the purpose of reference, the two rolls lying in the vertical plane may be referred to as the top and bottom rolls and the two in the horizontal plane as the side or lifting rolls. The bottom roll is supported from below on eight rollers, distributed in four pairs along its body, so as to be raised and lowered, and lies between the two side rolls. The latter

are supported at each end in bearings which are attached to motor driven jack screws, so that they may be raised or lowered along planes inclined to the vertical about 30 degrees. In order to prevent these side rolls from cambering on heavy work, each may be supported on rollers at its center by pressure from a constant pressure hydraulic cylinder, which is used as a follow up. The top roll is the driving roll and is supported by two special end bearings directly above the bottom roll, so that the plate, during the

FIG. 299. The Bending Machine Showing the bending of a plate, or skelp, for Hammer-weld Pipe. The Swing Bearing is shown in the left foreground.

bending, is gripped by these two rolls. One of these special bearings, known as a swing bearing, is anchored to the roll housing by means of a hinge and attached to a jack so that it can be moved or swung outward and downward and thus readily removed from the neck of the roll. The other bearing on the opposite end of the roll is a spherical bearing, which permits the top roll to be tilted inside of the main driving gear. The device used for tilting the roll is a hydraulic jack attached to a bearing on a prolongation of the neck of the roll. Thus, by lowering the swing bearing, the roll, by means of the overhanging bearing on the opposite end, may be tilted and supported while the bent skelp is being removed endwise from the rolls. The bottom and the two side rolls are seldom changed, but two sizes of top roll are employed, to better adapt the machine to the different diameters of pipe. The top roll is driven through a system of gears by a reversing motor.

Bending the Plate: In operating the rolls, the side rolls are lowered so that their rolling surfaces are on a level with or below the line of contact between the top and bottom rolls. Then, by revolving the rolls, the plate from the scarfing rolls, or, the cold plate unscarfed, is drawn into the machine until the top and bottom rolls lie along its center line. Now, by raising the side rolls slightly at the beginning of each pass and revolving the rolls, first in one direction then in another, the plate is gradually bent into the form of a pipe, and its edges are brought in contact. Since the bent plate is not turned through a complete revolution, a strip about six or eight inches wide along each side of the seam remains flat, and is an advantage in welding, as will be seen after the welding process is understood. As soon as the bending has been completed, the swing bearing previously described is lowered, and the long broad peel of an over-head charging and drawing machine is inserted between the top roll and the skelp. Then, by tilting the roll and raising the peel slightly, the skelp is removed endwise from the machine, and carried to the welding machine.

The Welding Machine: The method pursued in welding these large pipes consists in heating and hammer-welding a short section of the pipe at a time, and alternately repeating these operations until the joint has been completed. The apparatus for performing these operations are assembled to form a single unit, or welding machine, and consist of a carriage for supporting the bent skelp in the proper positions during the welding operations, a set of special burners for heating the sections of pipe, a horn and anvil for supporting the skelp from within while the heated sections are hammered, and a small power hammer for welding these heated sections and forging down the lap to a gage corresponding to the

Fig. 300. Two welding machines in operation. The machine on the right is designed to weld larger pipe than the one on the left.

rest of the pipe. This hammer, which is driven by an air cylinder, is mounted on a strong immovable frame from eight to twelve feet above the floor of the shop, according to the maximum size of the pipe the unit is expected to weld. Directly under the hammer is the anvil of the horn. This tool is constructed on the plan of a lever of the first class, and is made of a heavy nickel steel forging. The long arm, which must exceed the pipe in length, supports the anvil on its end, while the short arm is heavily loaded with weights to support the long arm and impart the inertia to resist and balance the blows of the hammer. Attached to this short arm is a small hydraulic jack for adjusting the horn during the successive welding operations. The heating apparatus is located about two feet in front of the hammer and anvil, and consists of two burners, one hung from the frame work of the hammer so as to be on the outside of the pipe to be welded, and the other supported on the inside by arms parallel with and back of the horn. Both burners are alike as to size and construction. Each burner consists of two parts, a metal base and a fire brick top. The latter contains, on its under side, an arched cavity, the top of which opens into a narrow slit that extends along the center line. The base, contains a number of small blow pipes arranged about two inches apart in two parallel rows along its longer axis. Over these burners is placed the fire brick top, secured with clamps and sealed with asbestos cement. The cavity in the brick thus forms a combustion chamber over the burners, the heat from which is concentrated along the slit in the top of the brick. The fuel used is water gas, which is burned with air supplied from a low-pressure blower, the pressure of the air and gas and the size of the burner openings being so regulated that the ratio of air to gas is about 3:1. The flame is thus kept but slightly oxidizing, in order to secure complete combustion and keep the amount of scale formed as low as possible. Since the hammer is supported in a fixed position, the carriage on which the pipe rests during the welding is mounted on a motor driven truck, in order that the pipe can be moved longitudinally to bring the heated sections under the hammer. The carriage is also provided with motor driven screws for lifting it to different levels, so that it may be adjusted to the different sizes of pipe. The arms of the cradle are provided with small rolls to give a roller bearing for the pipe, that it may be easily turned to and fro by means of bars and tongs in the hands of a workman.

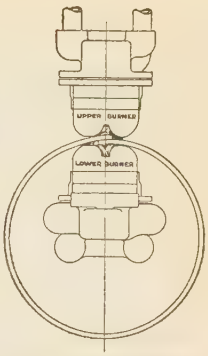


FIG. 301. Illustrating the method of heating the edges preparatory welding.

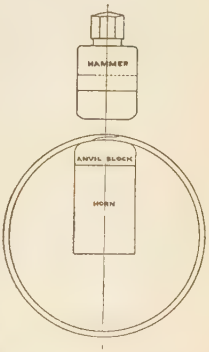


FIG. 302. Illustrating the welding of the heated edges under the hammer.

Welding the Skelp: The skelp is carried by the charging and drawing machine from the bending machine, moved endwise into the welding machine, and deposited on the cradle, which has been adjusted to the proper height for welding. The cradle is then moved back, bringing the bent skelp, with the seam up, over the horn until the latter extends through the skelp and projects from one end, which is now under the hammer. By bringing the hammer into action, the ends of the skelp are bent down until the two edges are in contact and lapped over each other. In general, the amount of the lap, which is controlled in the bending process, equals the thickness of the plate, but it is sometimes increased in an attempt to overcome a slight over-width in the plate. By moving the cradle in the opposite direction, this section at the end of the skelp is brought between the burners, which are adjusted to bring the heating slits within a short distance of the seam on each side. The gas is lighted, the blast is turned on, and, in a few minutes, the lapped section of the skelp is brought to a welding temperature. By moving the cradle, this heated section is brought beneath the hammer above, and over the anvil on the horn below. The latter being brought up against the hot part, the hammer is again brought into action, welding down the section and forging out the lap. These operations are then repeated, section by section, until the whole pipe has been welded. A welder and two or three assistants, depending on the size and weight of pipe to be welded, are required to operate the apparatus. From the nature of the operation it will be surmised that the welder must be an experienced and skillful workman. The amount of the lap, the temperature for welding, and the amount of forging necessary to bring the lap to gage are all essential attainments that can be determined only by the eye, and require very skillful manipulation of both the skelp and the apparatus.

Annealing and Straightening: When the welding has been completed, the pipe is removed by means of the charging and drawing machine, and carried to and charged into an annealing furnace. The plate is here heated to a temperature sufficiently high to remove all strains and refine the grain, when it is withdrawn with the charging and drawing machine and carried back to the bending rolls. Here, by lowering the swing bearing of the top roll and employing the overhanging bearing on the opposite end to support this roll in a slightly inclined position, the pipe is inserted into the machine by moving it endwise over this roll. Then, by lowering the end of the top roll, replacing the swing bearing, adjusting the bottom and side rolls to the proper height and revolving the top or driving roll, the pipe is made to revolve also. The action of the rolls tends to iron out all the irregularities in the surface of the pipe, and a few revolutions of the pipe suffice not only to impart the proper curvature to the section along the seam that was left flat and somewhat irregular by the bending and welding operations, but, also, to effect almost perfect rotundity in the pipe. This one machine, therefore, serves the triple duty of bending,

FIG. 303. Annealing Furnace with Doors Open to show Interior, and pipe in position for Annealing.

straightening and rounding, but as these operations take less time than that of welding, one bending and straightening machine is able to serve about four welding machines. This straightening operation also removes the scale formed during the preceding processes of manufacture.

Finishing Operations: After it has been straightened, the pipe is removed from the bending and straightening machine with the crane and placed on the floor to cool. When it has become cold, it is given a careful preliminary inspection, then subjected to such finishing operations as may be required to prepare it for service. The first of these operations consists in cropping the ends, which may be done with an oxy-acetylene torch, in a lathe, or in a specially constructed shear. Then, in case straight ends are required, the pipe is mounted in a special lathe, where the ends are trimmed with a tool, making their edges smooth and the planes of their circles perfectly perpendicular to the axis of the cylinder.

End Sizing: If great accuracy in end diameter is required for special work, the ends may be brought to exact diameter for a distance of a couple of feet back by forcing them over or within proper dies, mounted on the heads of a large hydraulic ram, which is known as the end-sizing machine.

As the preparation of the dies makes this an expensive operation, it is to be avoided if possible.

End Flanging: For pipe that is to be joined by any of the various types of joint requiring a formed end on the pipe, such as the straight and tapered bump joint, the spherical bump joint, the bell and spigot joints, the expansion joint, (shown in Figs. 306 to 311,) the Matheson joint, (shown in Fig. 297,) or the Van Stone joint, the special flanging machine, shown in Fig. 305, has been constructed for rolling the ends to the forms

FIG. 304. View of Sizing Machine on which the ends of each length of pipe are brought to the exact size requirements.

required. This machine is a very heavy and a somewhat complicated apparatus. The pipe to be flanged is supported upon a carriage so as to be moved longitudinally and turned circumferentially about its central axis. By means of a series of adjustable water-gas burners mounted in a circle directly before the rolling mill, the end of the pipe is first heated to a full red heat. Then the pipe, supported at a proper level, is pushed forward by a ram until its heated edge lies between the forming rolls of the mill, one of which projects into the pipe while the other bears upon it from below. By means of adjusting screws the rolls are brought to bear upon the pipe, which is started rotating at the same time the rolls are started revolving. The collars and grooves in the rolls form a pass of the exact contour required, and the action of the rolls on the rotating pipe soon brings the end to the shape required. Since the rolling is done hot, all brittleness and strains, such as are produced by cold working, are avoided.

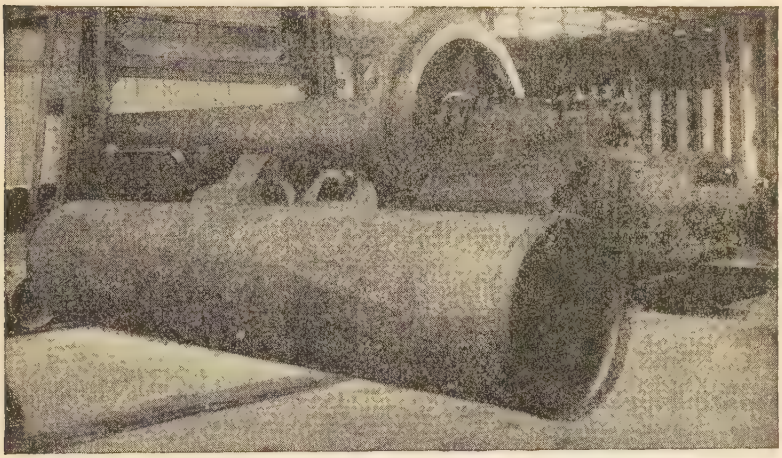
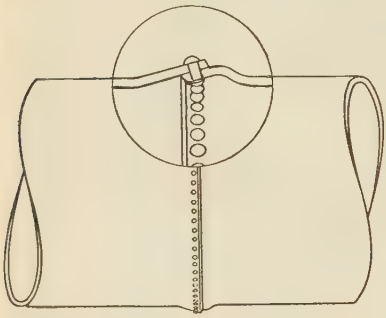


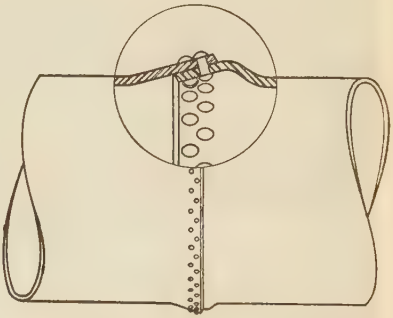
FIG. 305. View of Flanging Machine, on which the ends of the pipe are formed according to the type of joint desired.

Joints for Hammer-Weld Pipe: To illustrate the nature of the end-forming operations required on hammer-weld pipe, the following cuts of the different types of joints used with this pipe are shown (see Figs. 306 to 311). From these illustrations, it will be observed that screw joints are not employed with this pipe, the size of the pipe and the service to which it is applied, making such joints inapplicable. The joints used with this pipe, therefore, are of three main classes, which may be designated as flanged joints, bump joints, and bell and spigot joints. Of these the flanged joints and bump joints are generally used for steam lines and all high pressure work, and the bell and spigot joints for water and gas mains and low pressure hydraulic lines. However, by the use of the reinforcing ring shown in Fig. 308, the bell and spigot joints may be used for somewhat higher pressures. As to the flanged joints, the uses to which these are applied have already been explained in connection with ordinary lap-weld pipe. As will be seen from the illustrations, there are several different varieties of this joint, to adapt it to different wall thicknesses or to different kinds of service. No general statement as to the relative merits of these different varieties can be made. The bump joints, it will be noted from Fig. 306, are of three kinds, namely, the straight bump joint, the tapered bump joint, and the spherical bump joint, all of which require the ends of the pipe to be riveted together. The spherical bump joint permits the changing of the direction of the pipe slightly at the joints. The riveted bump joints are well adapted to high pressure lines. In surface lines, all the joints shown, require the insertion at suitable points in the line of expansion joints, such as that shown in Fig. 310, to take care of movements due to varying temperature conditions. In buried lines, there

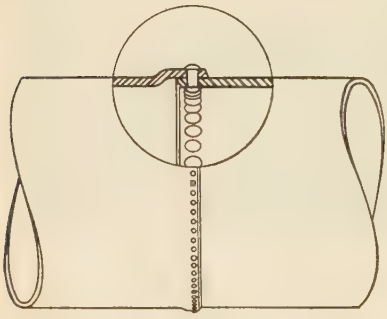
is no necessity to use expansion joints. The joints with the plain end coupling shown in Fig. 311, which is a rubber sealed joint, are about all the joints, which, up to 1925, had been developed for use with hammer-weld pipe.



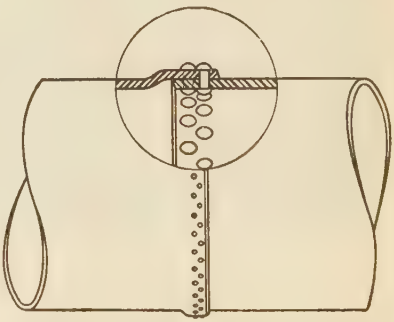
Tapered Bump Joint, Single Riveted



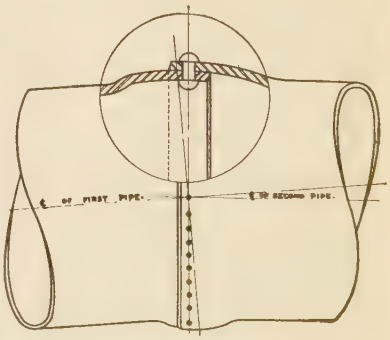
Tapered Bump Joint Double Riveted



Straight Bump Joint Single Riveted

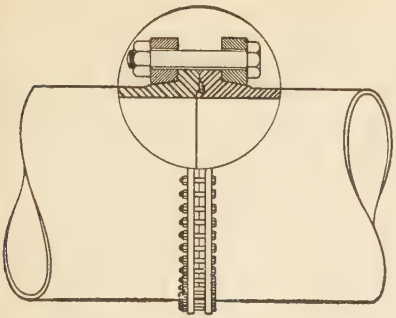


Straight Bump Joint Double Riveted

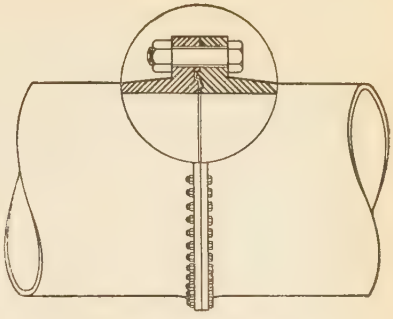


Spherical Bump Joint

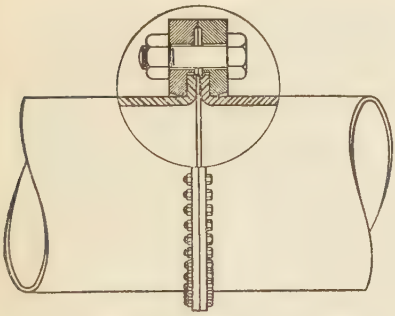
FIG. 306. Showing Assembly of the Different Types of Riveted Bump Joints for Hammer-Weld Pipe.



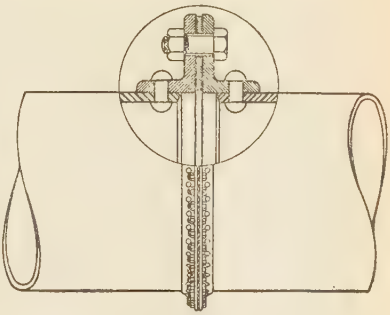
Welded Hub and Loose Flange Joint



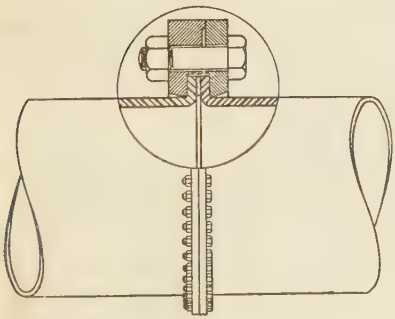
Welded Flange Joint



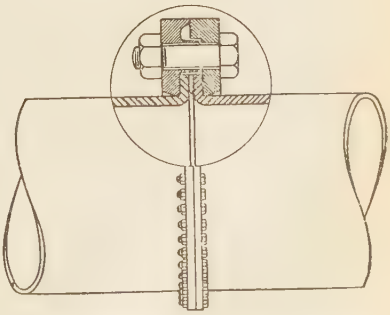
Loose Flange Joint for Light Walls



Riveted Flange Joint

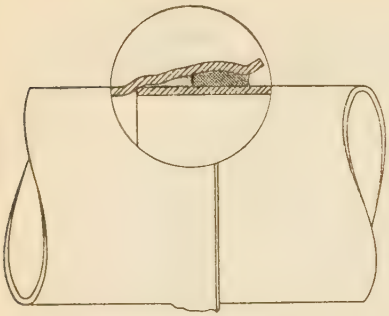


Loose Flange Joint for Heavy Walls

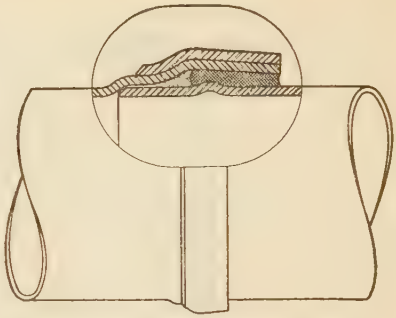


Loose Flange Joint for Medium Walls

FIG. 307. Showing Assembly of the Different Varieties of Flanged Joints for Hammer-weld Pipe.



Bell and Spigot Joint



Reinforced Bell and Spigot Joint

FIG. 308. Showing Assembly of the Two Types of Bell and Spigot Leaded Joints for Hammer-weld Pipe.

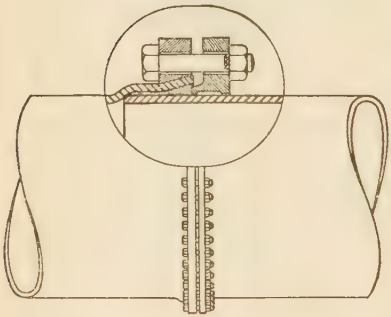


FIG. 309. Showing Assembly of Flange Bell and Spigot Joint for Hammer-weld Pipe.

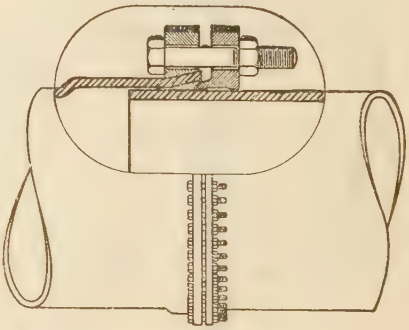


FIG. 310. Showing Assembly of Expansion Joint for Hammer-weld Pipe.

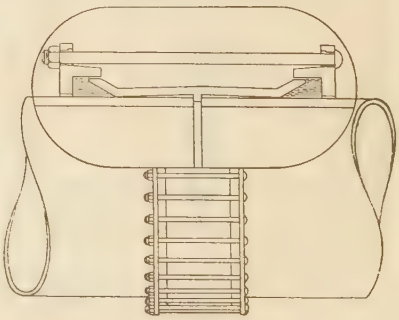


FIG. 311. Showing Assembly of Plain End Coupling Joint for Hammer-weld Pipe.

End-Welding: If double lengths of pipe are required, these can be made by welding two pieces together end to end. This work is performed by a hammer welding process similar in principle to that for welding longitudinal seams. The apparatus, however, must be considerably modified from that employed on longitudinal welding. To adapt the apparatus to different kinds of work, these modifications include a number of ingeneous devices, which must be arranged and manipulated in a certain peculiar way for each article made, and, on account of the large number of the articles thus fabricated, it is useless to attempt a detailed description of either the machinery or its operation here. A view of the machine in operation, welding the head on a still, is shown below. Besides permitting the end-welding of different pieces to form a single pipe, this apparatus makes it possible to fabricate complete tanks with hammer welded, flanged

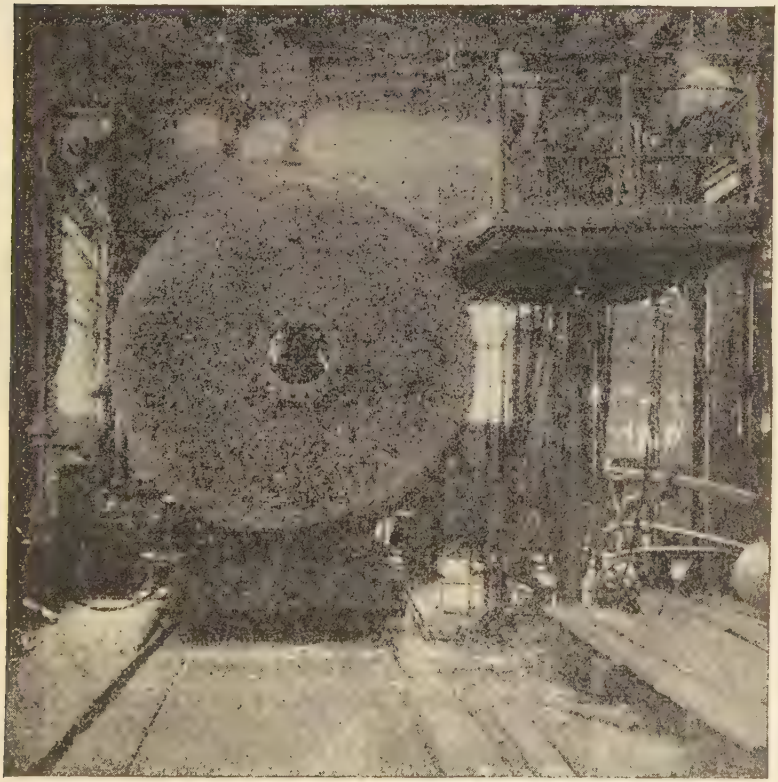


Fig. 312. Machine for Welding Girth Seams. This view shows the head of a 10-foot still being welded to the shell.

and dished heads, also stills, digestors, dephlegmators, heat exchangers, expansion chambers, etc. Even the nozzles, if not too small, may be welded to these vessels, thus totally eliminating riveted joints and making these vessels as water-and gas-tight and practically as strong as if they were moulded from a single piece of metal.

Fig. 313. Hammer Welded Dephlegmator. 42 inches I. D. with welded flange and nozzles. The insert gives a close-up view of the weld joining one of the nozzles to the shell.

Inspecting and Testing: Following the last finishing operations the work is given a final inspection. In the case of pipe each length is subjected to the internal hydrostatic pressure test. For this purpose it is placed between the heads of a very large horizontal hydrostatic press, where, by pressing the ends against packing rings of bearing metal, leather, or other suitable packing, the joints between the ends of the pipe and the heads are made water tight. Then water is admitted until the air has all been displaced and the pressure has been raised to the amount desired. This pressure varies from 150 to 2000 pounds per square inch, according

to the size and wall-thickness of the pipe and the service for which it is intended.

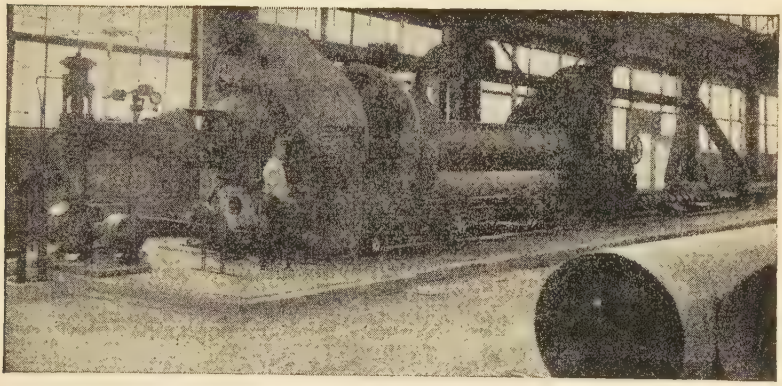


FIG. 314. View of Hydrostatic Testing Machine in Operation.

After testing, the pipe is thoroughly inspected as to surface finish and dimensions. Then, if desired by the customer, the pipe is given a protective coating as described under ordinary lap-welded pipe. Finally, it is stenciled with the name of the manufacturer, the pressure applied in testing, and any other marks necessary to identify it, when it is ready for storing or shipment.

SECTION V.

THE SEAMLESS STEEL TUBULAR PRODUCTS.

Historical: Although the modern methods for manufacturing seamless or weldless steel tubes have been developed since 1890, a period of little more than thirty years, they are, nevertheless, the result of nearly a century of experimentation. As mentioned in the introduction to this chapter, the first attempts to make seamless tubes of steel that were commercially successful involved the two basic processes known as cupping and piercing. In the cupping process, which was first used about 1845, a circular sheet or plate was forced by successive operations through several pairs of conical dies, each pair being deeper and more nearly cylindrical than the previous one, until the plate took the form of a tube, or cylinder, with one end closed. This method is still in use for certain sizes. In the piercing process, a round hole was first made along the central axis of a round billet which was then rolled and drawn over mandrels to form a tube. The mill for lengthening such hollow billets was first patented in England by Church and Harlon about 1841. The rolling mill and the draw bench afforded simple and comparatively cheap methods of elongating the hollow billet, but the development of a method for piercing it proved a difficult matter. The oldest and simplest method was to heat the billet to a high forging temperature and hydraulically force a punch through its center while in this hot state. As it was essential that the hole be exactly concentric with the billet throughout its entire length, a feat that is hard to accomplish with a billet more than a foot or so in length, recourse was had to drilling a small hole in the billet cold, then heating the billet and enlarging the hole by piercing in a press. About 1888 a patent was granted for a process whereby a small ingot was cast about a core of refractory material, which hollow ingot was to be treated as described for hollow billets. So far as the manufacture of pipe and tubes are concerned, all these methods of piercing have now been replaced by two methods, known as the Mannesmann, or roll piercing, and the Stiefel, or disc piercing process, which will, therefore, be explained somewhat in detail.

The Mannesmann Machine for piercing round billets for making seamless tubes was patented in 1885. It embodies the principle of diagonal rolling, which at the time proved to be a somewhat startling innovation. This principle can be carried out in a number of different ways with rolls of different shapes, but only the manner in which it is employed at the present time will be described. The rolls used in this machine are comparatively heavy. They measure, over all, about thirty-six inches, and,

in the body, or face, twenty-four inches in length, and from thirty-two to forty inches in diameter. Their diameters are varied according to the size of tubes to be made; a thirty-two-inch roll is the size most suitable for all tubes up to four and one-half inches in size, while a thirty-six-inch roll is employed for sizes between four and one-half and nine inches. Their shape resembles that of a piece cut from the middle of a very large spindle with a flat portion about one inch long at the middle. From this flat part each roll tapers toward each end at an angle of 5° to 10°. This angularity of the rolls is necessary to produce the play of forces required to effect the piercing and at the same time permit the billet to be drawn continuously through the mill. These rolls may be made of steel or adamite, and are made with necks like an ordinary roll but are provided with a type of universal joint instead of wobblers. When they are placed in their housings, they lie side by side instead of one above the other, and their axes are set slightly askew and inclined, each at an angle of 6° to 12°, in opposite directions, so that the rolls cross each other at their centers. Upon the amount of this angle depends the speed with which the billet will be drawn through the mill. They can be adjusted laterally in their housings, and are set so that the distance between their rolling surfaces at the middle is a definite amount less than the diameter of the billet to be pierced. The rolls are driven by an electric motor located some twenty feet from the housings on the entering side. The power required varies from 700 to 3000 horse power, depending upon the size of the piercer. By

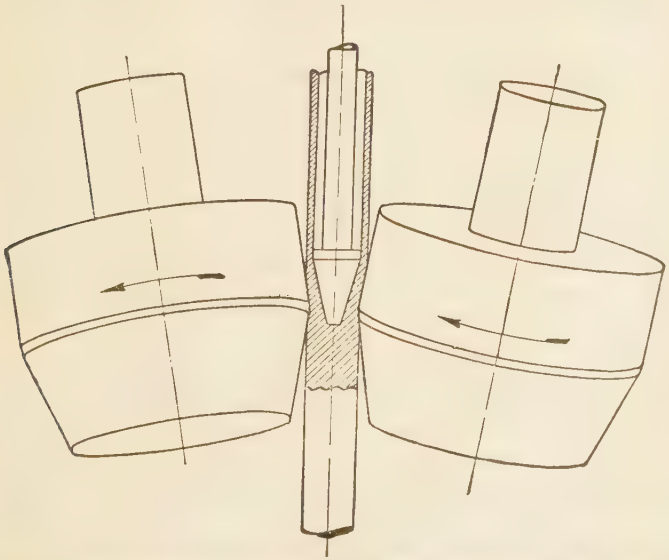


Fig. 315. Illustrating Arrangement of Rolls and Mandrel and the Principle of Diagonal Rolling Employed in the Roll Piercer.

means of a system of gears and two long spindles, the rolls are driven, both in a clockwise direction, at a speed of about 90 r. p. m. Sprays of water are provided to keep the rolls cool while in use.

The Operation of Piercing: Although the action of the rolls is far from being as simple, the piercing is performed apparently with as much ease as any ordinary rolling process. A round billet, of the proper length and diameter to make the size and length of tube desired, is first centered on one end to a depth of about one inch, and is then heated uniformly to the usual temperature for rolling light sections. Next, a mandrel, or plug, with a pointed nose, tapered at the proper angle and known as the piercer, is attached to a water cooled rod designed for the purpose, and inserted between the rolls from the delivery side, so that its pointed end just passes the line where the rolls cross. With the rolls revolving at a constant speed, the heated billet, lying in a trough, is now pushed, centered end first, into the space between the rolls by means of a rod actuated by a hydraulic or compressed air cylinder. The rolls immediately grasp the billet, revolve it rapidly, and pull it slowly forward, while at the same time they draw the metal away from the center to form a hole, elongate and enlarge this hole, and force the metal over the plug and rod, which,

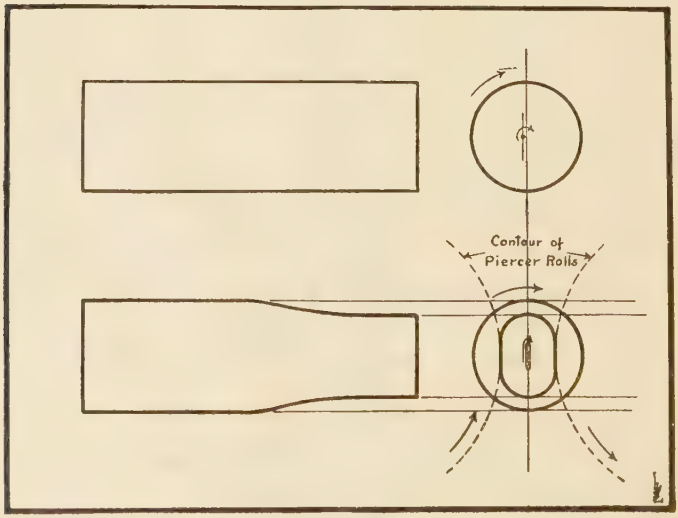


Fig. 316. Sketches Illustrating Action of Rotary Piercing Mill on the Round Billet.
Top Section of billet and direction of rotation on entering mill.
Bottom. Section of billet and action of Rolls in producing cavity.

while they revolve in a thrust-block bearing at the same rate as the billet, maintain the same relative position with respect to the rolls. Less than a minute is required to perform this composite operation. When the billet issues from the mill, having been forced entirely over the mandrel, or plug, it is in the form of a thick walled tube, somewhat rough on its surface but fairly uniform as to thickness of wall.

The Action of the Rolls is somewhat difficult to understand and still more difficult to explain satisfactorily. It is evident that the forward motion of the billet is caused by the inclination of the axes of the rolls. How these two rolls, by exerting pressure only on the surface of the billet, are able to force the metal over the mandrel to form a tube from a solid billet is not so readily grasped. It is to be especially noted that the mandrel is not forced through the metal, but that the rolls cause the metal to flow over and about the mandrel. To bring about this result, the rolls must first draw metal away from the center of the billet, which action forms, or tends to form, a central hole, or cavity, for the passage of the mandrel, or piercer. The truth of this statement is evident from the fact that a small, but somewhat irregular, hole may be formed in a billet without the use of the piercer.

The Principle Involved in Forming the Cavity: Indeed, such a hole can be opened up in the center of any solid cylindrically shaped plastic body by rolling it between, even, two flat surfaces. Steel workers, particularly hammermen, are familiar with the fact that, if a piece of steel in the form of a round be pressed or hammered into an oval form several times in succession, a rupture will occur in the center that will extend longitudinally through the middle of the bar. The reason for the formation of this rupture is plainly due to the fact that when pressure is applied to the round bar at diametrically opposite points sufficient to deform it, making one diameter shorter and that at right angles to it longer, the spreading of the metal, which takes place along the long diameter and in opposite directions, sets up a lateral tension that may cause its particles to be drawn away from the center.

Flow of the Metal in Piercing: This is the action that first occurs in the roll-piercing machine. As the billet, which is in a plastic state, enters the mill, the rolls grasp it at diametrically opposite points on its circumference while it is yet about four inches from their centers. As they draw the billet forward they continue to compress it at these opposite points, and since they revolve it rapidly, these points are continually changing. In this way a small hole is quickly formed, and is then rapidly enlarged. This enlargement is due to two things. As the rolls are larger at their centers than at the ends or the points at which they grasp the billet, the increasing peripheral speed tends to produce a twisting action

on the outer surface of the billet between these two points, and, as their axes are inclined to the axis of the billet, they at the same time exert a forward pull upon the outer surface of the billet. The result of this double action is that the metal is forced to flow in a spiral path, and, since the decrease in the diameter of the bar is not sufficient to compensate for this increase in length, metal must be withdrawn from the center to compensate for the deficiency.

Function of the Mandrel: This opening is further enlarged by the rolling-on process that occurs as the hollow part of the billet is forced over the mandrel, or plug. This rolling-on process increases the diameter, hence decreases the thickness of the wall. As pointed out in a former paragraph, it is the practice to place the piercer point a little beyond the centers of the rolls. This position is necessary in order that the billet may be forced entirely over the mandrel before it passes from between the rolls, as otherwise the piercer point would remain imbedded in the metal. In this position the piercer point probably does some work, but the action of the rolls is the main force in pulling the metal away from the center. Since the mandrel cannot be held to an exact center to start with and it is desirable to start the rolling-on before the opening in the center is very large, the forward end of the billet is centered to insure that the point of the mandrel will penetrate the billet at or very near its axis. Centering is not absolutely necessary, but it probably lessens the power required to start the rolling-on process, and reduces the wear on the piercer point. At the end of the rolling, the mandrel bar is removed from the tube which encircles it, and the mandrel, which drops from its end, is plunged into water to cool. The process can then be immediately repeated by placing another cold mandrel on the bar as before.

The Stiefel Machine, an American invention, was patented in 1895, and up to 1918, it was the only machine used by the National Tube Company for piercing billets. The rolls for this machine, two in number, and of the same shape, have the form of large discs, and are about thirty inches in diameter. The rolling faces of these discs are bevelled, or chamfered, at an angle of about 7½° for a distance from the edge equal to nearly half the radius. These two discs are mounted on the ends of two shafts that lie in two parallel lines and extend from two points in opposite directions. The distance between the centers of the shafts produced is about two-thirds of the length of the diameters of the discs. In this way only sections of the two discs, corresponding to a little less than two-thirds of their diameters, face each other. These sections are the working surfaces of the discs, and are separated by a space slightly less than the diameter of the billet to be pierced. Each shaft is connected through gears to a main driving shaft, propelled by a steam engine or electric motor, so that both discs are revolved in the same direction and at the same rate. Between

the discs and extending beyond the mill on both sides, is a trough for supporting the billet during the piercing process. This trough is fixed in a position to cause the billet to enter the mill between the discs on a level a little below their centers of rotation and along a line slightly inclined to the base plane of each.

The Operation and Action of the Mill: Like the Mannesmann machine, the operation of the Stiefel mill is very simple. The billet, which has been previously centered, is heated to a uniform forging temperature, the plug, or mandrel, supported on the end of a bar, is put in position between the discs from the delivery side, and the billet is shoved into the mill from the opposite side by means of a mechanical pusher. Like the rolls of the Mannesmann mill, the discs grip the billet, revolve it rapidly, pull it forward, draw out the metal to make a hole in the center, and force the wall of the rough tube thus formed over the mandrel. The effect upon the metal produced by the discs is also similar to that of the rolls, with the exception that, whereas, with the Stiefel disc piercer, the spiral flow of the metal is more noticeable on thin-walled piercings than on heavy-walled ones, with the Mannesmann roll piercer this effect is about the same on thin- as on heavy-walled piercings.

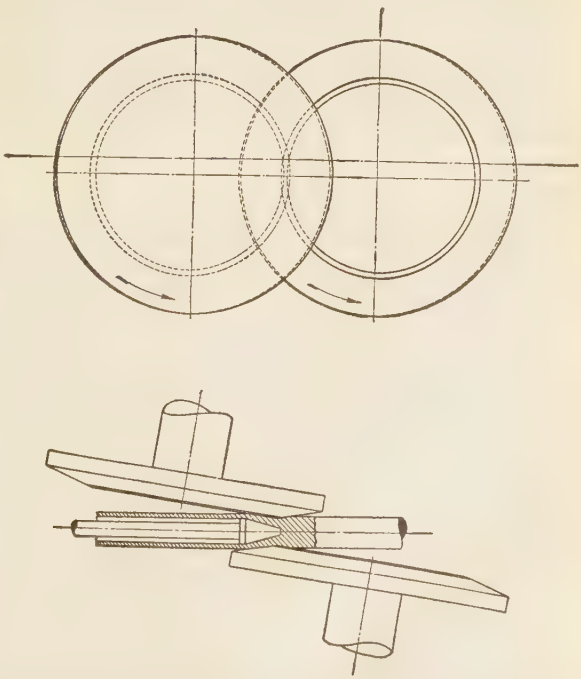


Fig. 317. Drawing Illustrating Principle of the Disc Piercer, or Stiefel Machine.

A Comparison of Processes: It is evident that the steel is subjected to very severe distortion in both these processes, and only billets of the best steel, absolutely sound and of uniform material, and heated to a uniform temperature throughout can be used. With such material, these mills pierce billets as accurately as it can be done by any other method, giving a wall of uniform thickness. This feature is very important in seamless tube making, because it is difficult to remove any variation of this kind by any of the subsequent operations. Neither mill can be used to pierce billets much less than three inches in diameter, but by subsequent rolling and drawing processes the size may be reduced to the smallest required. The disc-piercing mill cannot be constructed as rigidly nor be made as strong as the roll-piercing mill, and the latter, therefore, is better adapted for heavy work. With the roll-piercing machine, it is the general practice to make seamless tubes up to 9½ inches in diameter.

Steps in the Making of Seamless Tubes: As has already been indicated, the piercing of the billet is but one of several steps necessary in the making of seamless tubing, the first of which is the making of the steel itself. Then comes the casting of the steel into ingots, and the rolling of these into rounds, which are cut into lengths, centered, and heated before the piercing can be done. The piercing is followed by rolling, reeling, and sizing processes to produce hot finished tubes, and to these is added cold drawing to make cold finished tubes. The details connected with the carrying out of these processes vary somewhat, and it is best to describe some one modern plant as an example of the best practice. As such an example the Ellwood Works of the National Tube Company has been selected, and the description that follows is that of the practice followed at this plant.

Preparation of the Billets: Only steels carefully made by the open hearth or the electric process are used, because these grades have been found to withstand best the severe distortion the steel is subjected to in the various processes of manufacture, especially in the piercing operation. Since there are, as yet, no furnaces at Ellwood, most of the steel is made in basic open hearth furnaces at Lorain, Ohio. Special care is taken to see that the steel is thoroughly deoxidized in the furnace and that the sulphur content does not exceed .050 per cent. The ingots produced are rolled on a reversing blooming mill into blooms six, seven, eight, and ten inches square, and, after a generous discard to eliminate pipe and segregation has been made, these are cut into lengths of about eleven feet, each being stamped with its heat number. These blooms are then carefully inspected, and all surface defects are shipped out with pneumatic chisels. They are then loaded in cars and shipped to Ellwood Works to be rolled into round billets.

Rolling the Billets: For this purpose a 22-inch mill of the continuous type is employed. It consists of five stands of rolls set far enough apart to allow the piece to clear each stand before entering the succeeding one.

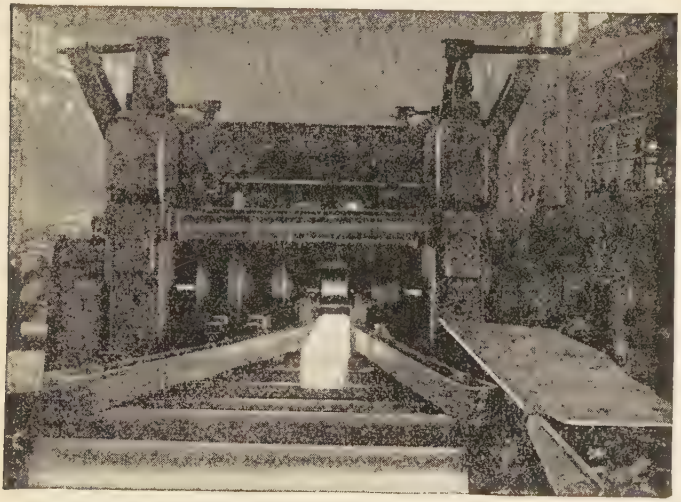


FIG. 318. View Showing the square bloom entering the first stand of the rolling mill.

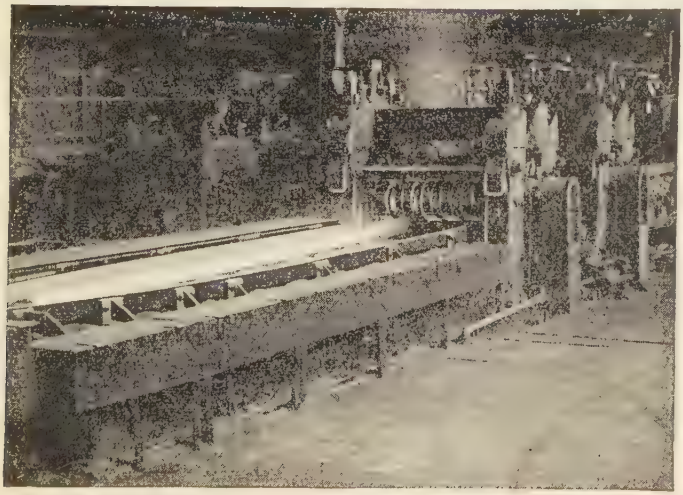


FIG. 319. View Showing the round leaving the last stand of the rolling mill.

It is driven by a motor of about 800 horse power, by means of cross-over shafts and bevel gears, from a single drive shaft, in the usual manner for such mills. At the entering end, it is served by six large heating furnaces of the regenerative type, arranged in a long row, end to end; and on the finishing end, by three hot saws. Two electric charging machines, one of the overhead and the other of the floor type, are used for charging and drawing the blooms and transferring them to the receiving roll table. The bloom passes straight through the five stands of rolls, being turned between passes by means of collared rolls, and is thus gradually worked down to the size desired. Four different roughing and seven finishing passes are provided in the mill, which permit the rolling of four sizes of blooms and several sizes of billets without changing the rolls. The size of the latter vary, according to the size of the tubes or tubing to be made from them, from three to eight inches. The mill does not produce a commercially round bar with all diameters equal, as an exact round is not necessary in the process.

Cutting and Centering the Billets: From the finishing stand, the round billet or bloom passes to the hot saws, where it is cut into pieces, which must vary with the length and wall thickness of the finished tube. As the billets are sawed off, they roll down to the base of an inclined bed, to be placed as desired into the trough of the centering machine. At one end of this trough is a movable stop which shoves the billet endwise against the head of a pneumatic hammer, and holds it there while the hammer drives a center

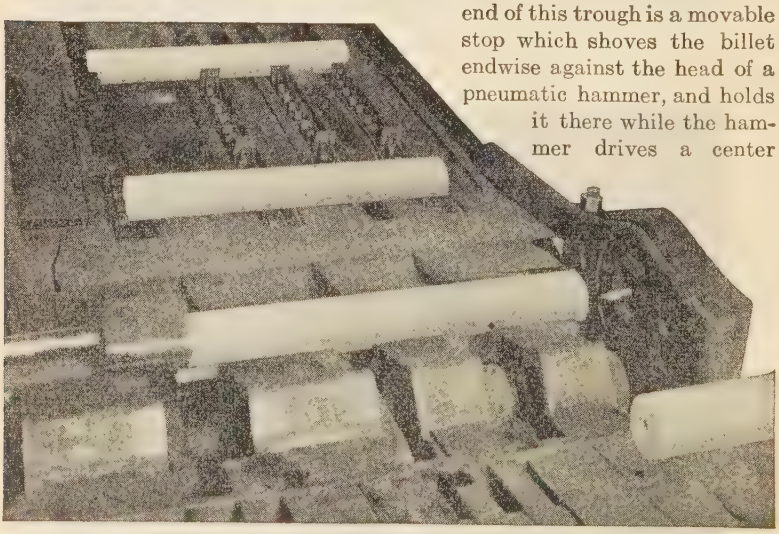


Fig. 320. Showing the Centering Machine in operation.

punch into its end, entering it to a depth of about one inch. The hot billet, thus centered, is then carried up an inclined table with endless chains and dropped into a cradle, which is removed, when filled, to the yard, where the billets are allowed to become cold. They are then carefully inspected for surface defects, stamped with the proper die for identification, and sent to the piercing mill.

Piercing the Billets: At the piercing mill, the billets are charged into a continuous furnace, the bottom of which is inclined just enough to permit the round billets to roll by gravity toward the hot end, as rapidly as they are removed therefrom. In this way, the billet is heated gradually and uniformly. As soon as the billet has reached the proper temperature, which may be described as a high forging temperature, it is removed from the furnace with tongs and dropped on a short inclined table, down which it rolls into the feed trough of the piercing mill. It is then pierced by either the roll- or the disc-piercing mill, as previously described. Issuing from the piercing mill, the pierced billet presents the appearance of a very rough, short tube, with certain marks produced by the piercing rolls plainly visible on its surface. The walls of this rough tube are somewhat too thick, and it is the object of the next operation, a rolling-on process over a mandrel, to decrease this thickness by elongating the wall of the tube. Accordingly, when the piercer rod, which the rough tube

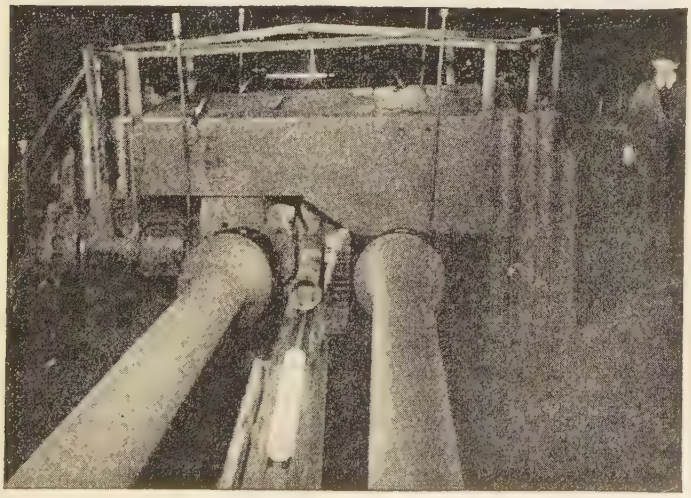


Fig. 321. The Roll Piercer, Entering End, showing billet entering mill.

encircles during the piercing operation, has been withdrawn, the tube is lifted by mechanically controlled fingers out of the receiving trough of the piercing mill upon a short inclined table, down which it rolls to another trough before the rolling mill. The piercing operations require the constant attention of three men, a roller to feed and control the mill, a plug setter to attend to the mandrels, and a bar puller to withdraw the mandrel bar and transfer the rough tube to the rolling mill.

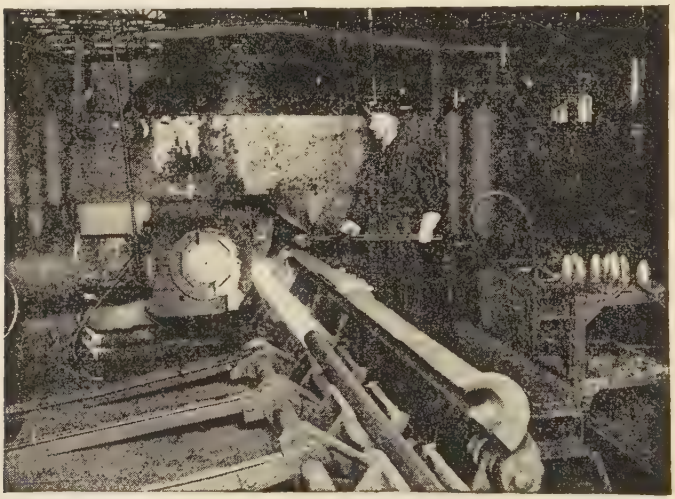


FIG. 322. The Roll Piercer, Delivering End. Showing Pierced Billet coming out of the Mill.

The Rolling Mill: The rolling mill, a 22- or 24-inch mill that resembles the old time drag over mill set up for rolling rounds, is a motor driven, non-reversing, two-high stand with grooves cut in the rolls similar to those employed for rolling hand rounds. Electrically operated screw-downs through the tops of the housings, which are of the closed top type, and suitable counterweights beneath, provide a means of quickly and accurately adjusting the top roll. Instead of roll tables, the mill is equipped on the entering side with a movable trough and pusher, and, on the delivery side, with a stationary guide table and mandrel rod support. The guides on the latter table, four or more in number, are of the double bell type, and are mounted on cross beams, so that they may be adjusted transversely and lined up one behind the other directly in back of any pass in the rolls. The mandrel rod, anchored in the support at the rear of the table, projects through these guides into the roll pass of the mill. Since it is necessary

to pass the tube more than once through the mill, some means must be provided for removing the tube from the mandrel bar and returning it again to the entering side. For this purpose a set of two small pull-off rolls is placed between the guide table and the large roll stand. These rolls are about twelve inches in diameter and very short, as they contain but a single groove. They are mounted one above the other on shafts which have their bearings in housings located in line with those of the mill. The rolls revolve in directions the reverse of those of the large rolls, and one shaft can be raised and lowered, thus bringing the rolls into play upon the tube only as it is desired to do so.

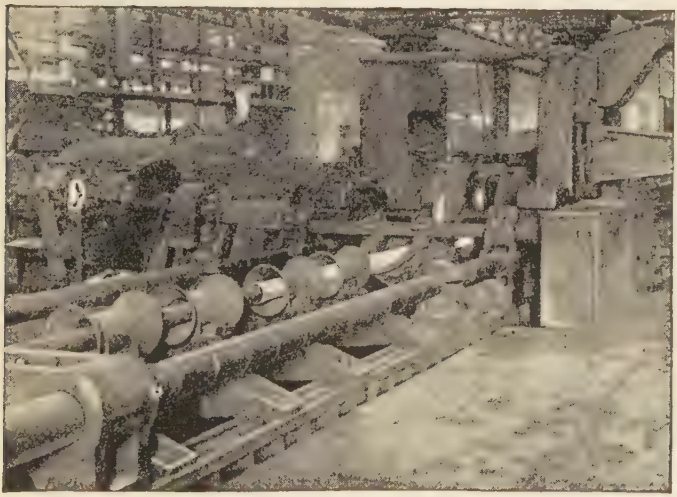


FIG. 323. The Rolling Mill, Mandrel Side, Showing mandrel bar and guides with tube passing through the mill.

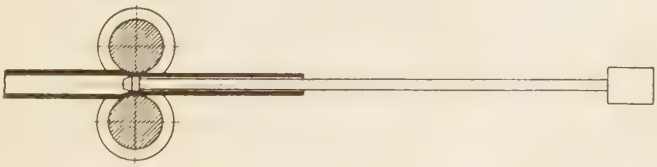


FIG. 324. Diagram of the Operation of Rolling the Tube.

Rolling the Rough Tube: With this equipment, the rolling of the rough tube can be expeditiously performed by three men, a controller, a ball setter and a roller. With the rough tube from the piercing mill lying

in the feed, or delivery, trough, the ball setter attaches a mandrel, or ball, made of adamite, to the end of the mandrel rod, which holds the former at the correct position in the roll groove. The tube is then shoved into the pass, by means of a mechanical pusher, with considerable force, in order to start it over the mandrel and permit the rolls to secure a good bite upon it. Once started, the forces of friction due to the pressure exerted by the revolving rolls is sufficient to force the tube rapidly over the mandrel. As soon as it has passed through the groove, the mandrel is removed from the bar, the top roll is raised an inch or so, and the small pull-off rolls on the delivery side are brought to bear on the tube, which is returned by them to the entering side of the mill. Another mandrel, slightly larger, is now placed on the bar, and the roller, turning the tube through an angle of 90° to roll down the diagonally opposite over-fills formed in the first pass, again starts the tube through the mill. The tube is again returned and given a third, and, if necessary, a fourth pass through the mill in a similar manner. In this way, the wall of the tube, supported by the mandrel from the inside and subjected to the action of the rolls on the outside, is reduced in thickness to the gage desired, and the tube is proportionally lengthened and slightly reduced in outside diameter. The tube now has a uniform wall of the desired thickness throughout, but it is slightly out of round, or oval shaped, not perfectly straight and, being still at a bright red heat, is covered with an ever increasing coat of scale. The tube, therefore, is rolled down another table slightly inclined, to the trough of a reeling machine.

Reeling the Tube: The reeling machine consists of a pair of short heavy rolls, size about 30 by 34 inches, of special design, set in housings so as to lie side by side with their axes inclined a few degrees to the horizontal and in opposite directions, and with the rolls crossing each other at a corresponding angle exactly in the middle of their length. The rolls are separated by a space but a few thousandths of an inch less than the diameter of the tube to be reeled, and their surfaces are so curved, their edges being beveled and their middle slightly concave, that if a tube were placed in this space, it would be in contact with the surfaces of both rolls for several inches of its length. Each roll can be adjusted laterally to a thousandth of an inch. The rolls are motor driven, and are geared together to revolve in the same direction at a fairly high rate of speed. To operate this machine, a mandrel, supported on the end of a specially designed rod, is shoved into the space between the rolls, and the tube, which, as received from the rolling mills, must still retain enough heat to make it a bright red in color, is mechanically pushed in over the mandrel from the opposite side of the mill. Since the rolls are revolving in the same direction, they start the tube and mandrel revolving also, and as their axes are inclined to each other, they slowly draw it forward over the mandrel. During the rolling, the tube and mandrel are supported from below in the hori-

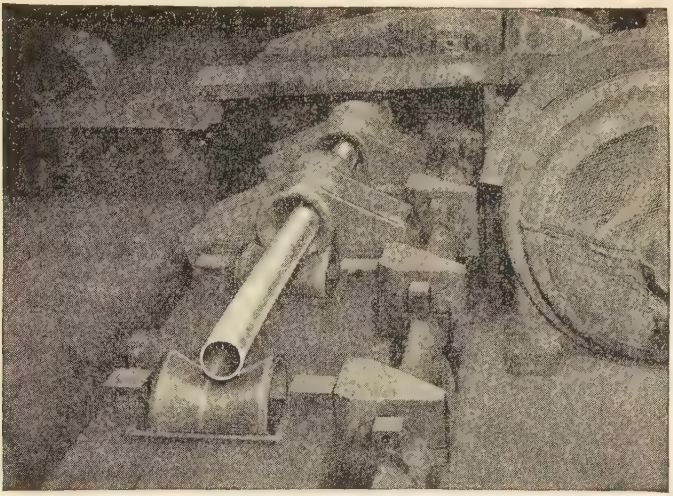


FIG. 325. Showing Tube entering the Reeling Machine.

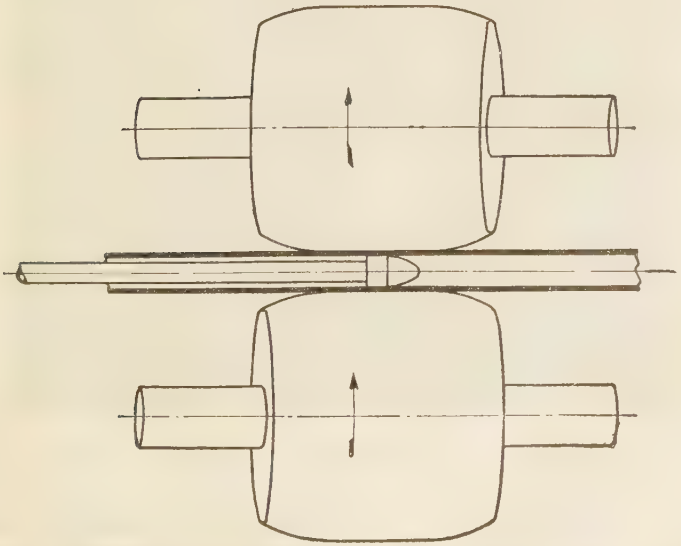


FIG. 326. Form and Arrangement of Rolls for, and Principle of Reeling Machine.

zontal position by properly shaped guide shoes, and the former is kept down on these bearings by a downward push exerted by one of the rolls. This force is created by making the peripheral speed of the particular roll whose acting face travels downward slightly greater than the other roll whose opposing face travels upwards. Owing to the slow rate at which the tubes are drawn through the rolls, two machines are required to serve one piercing and one rolling mill. As the tube comes out of this machine, it is practically straight, perfectly round, is slightly enlarged in diameter, and has a smooth, burnished surface. But it must receive one more operation—that of sizing. After the mandrel bar has been withdrawn, therefore, the tube passes on to the finishing rolls.

Sizing the Tube: The manner of finishing and sizing the tube now depends upon the finished size desired. For sizes three inches and over, the finishing process consists merely of passing the tube, reheated if necessary, through sizing rolls similar in construction and operation to those used in lap- and butt-weld mills, which give the exact outside diameter required. But, since the smallest size that can be economically produced by the piercing, rolling and reeling method employed in this plant, is three inches, the production of hot finished tubes less than three inches in diameter

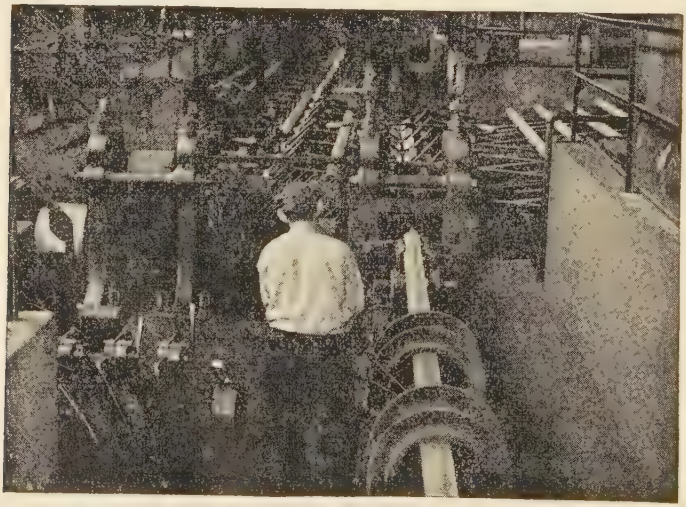


FIG. 327 Sizing Rolls—Showing reheated tube passing through the rolls.

requires a sinking and sizing process, for which a special machine is employed. This machine is a kind of rolling mill. It consists of twelve stands of two-high grooved rolls, about twelve inches in diameter, arranged on the continuous plan and set about two feet apart, center to center.

Instead of standing vertically, the housings for these rolls are inclined 45 degrees, so that adjacent stands lie at right angles to each other, and the loci of the centers of the openings formed by the grooves, which gradually decrease in size from first to last, are in the same straight line. The first grooves may be slightly oval in shape, but the last few passes are perfectly round. As the tube from the reeling machine is too cold to be handled on this machine, it is passed endwise into a long reheating furnace, located at the entering end of the mill, and heated to a temperature just below the scale-forming point, being turned a few times to make this temperature uniform. It is then pushed directly into the first stand of sinking rolls, when it is drawn straight through the mill, being elongated and reduced in size to the exact outside diameter desired, within the limits of the mill. The smallest size to which the tubes are usually reduced by this process is 1½ inches. By properly regulating the speed ratios of the different stands of rolls, the elongation is made to compensate almost exactly for the decrease in diameter, and the thickness of the wall remains unchanged or is very slightly increased.

Finishing Operations for Hot Finished Tube: Being thus rolled at a temperature below the scale forming point, the tube leaves the sinking and sizing rolls with a partly burnished surface that cannot be spoiled by any further formation of scale. On the other hand, since most of the reduction in size is effected in the first six or eight passes while this tube is still at a red heat, it has none of the brittleness incident to cold working, and is slightly stronger than a full annealed tube would be if made of the same steel. Having been constantly worked as it cooled to the critical range, the tube has a uniform and fine grain structure, as shown by photomicrograph No. 1 (Fig. 335, page 1107). The tubes are cooled as they come from the sizing rolls on a long inclined table, up which they are slowly rolled by means of endless chains. They are then inspected and sorted, and transferred by electric cranes to various cutting-off machines where the crop ends are removed and the remainder cut, if necessary, to the lengths required. If some of the tubes have become slightly crooked in cooling or handling, they are straightened, when they are all inspected again, tested, and made ready for shipment.

Accuracy of Hot Finished Tubes: As to the accuracy of the dimensions of hot finished tubes produced by these processes, the tolerances allowed the manufacturer by the standard specifications for hot rolled seamless boiler tubes indicate in a general way what can be accomplished in this line. These tolerances, which vary with the size of the tubes, are as follows: The weight per linear foot of tubes under 3½ inches outside diameter shall not vary more than 5 per cent. above or below the weight specified. Tubes 3½ inches and larger in outside diameter may vary 7½ per cent. above and 2½ per cent. below the weight specified. Finished

tubes 3½ inches or under in outside diameter shall be circular within .02 inches and the mean outside diameter shall not vary more than .015 inches from the size ordered. For tubes over 3½ inches outside diameter, these variations shall not exceed 0.5 per cent. of the outside diameter. The thickness (of the wall) at any point shall not exceed 3 gages above and none below that specified, but in all cases the weight shall be within the variation specified. It is well to emphasize here that, due to the limitations inherent in the piercing, rolling and sinking apparatus, tubes less than 1½ inches in size, outside diameters, and tubes with a wall thickness less than three per cent. of the outside diameter or with a wall thinner than 11 gage (.120 inch) ordinarily cannot be hot finished. There are a few exceptions to this statement, but these tubes require special consideration and, usually, some modifications from the ordinary practice.

Cold Finishing Tubes: Following the sizing operations just described, the tubing may be subjected to additional finishing processes by cold drawing, when it is designated as cold finished or cold drawn tube or tubing. In general, cold drawing is employed to produce tubing with lighter walls than can be made hot finished; to reduce the tubing to sizes smaller than can be made by hot working; to change its shape to something other than round; to secure a smooth, bright scale-free finish on its surface; to increase its strength and stiffness; or to secure closer approximations to accuracy in wall thicknesses and diameters than is possible in hot working. At the Ellwood Works, all tubes under 1½ inches in size are finished to size by cold drawing, and any tube from ⅛ inch to 9 inches in size may be so finished, though ordinarily the largest size cold drawn is six inches.

Principle of Cold Drawing: Both the principle and operation of cold drawing are very simple. The process consists of pulling the tube through a ring shaped die or collar, the smallest internal diameter of which is somewhat smaller than the diametrical cross section of the article to be drawn. The frictional resistance offered by the metal to being pulled through the opening increases the pull to beyond the elastic limit, when the material is rendered plastic. Hence it is continuously being stretched in the die, which elongation produces a corresponding decrease in the cross section until the latter is as small as the exit, when it slips through. It is evident that the draft may be increased only up to a certain limit, which is limited by the ultimate strength of the section leaving the die, for if the resistance and the balancing pull should exceed this stress, the article would break after leaving the die. It is just as evident that, for effective work in elongating the article and reducing its section, the pull must exceed the elastic limit of the section at the point being drawn. The strength of the die and pulling machine should, therefore, be proportioned to the work in hand.

The Draw Bench: For tubes, the apparatus used consists of a heavy steel bench, in the middle of which is fixed a frame or holder for the die.

At one end of the bench is a holder for a mandrel bar, and at the other is a strong sprocket wheel which is geared to some suitable source of power. Over this wheel, is placed a heavy, square-linked endless chain that travels from the die along the top of the table to the sprocket wheel and returns under the bench and over another wheel placed beneath the die. A set of tongs, for grasping the end of the tube, is carried on one end of a small truck, which is provided at the other end with a hook for engaging the endless chain. The total length of these benches vary from thirty to eighty feet, and they may be used to draw tubes from twelve to thirty-six feet long, finished length. The die, and the mandrel sometimes used in connection with it, are made of very hard crucible or electric steel.

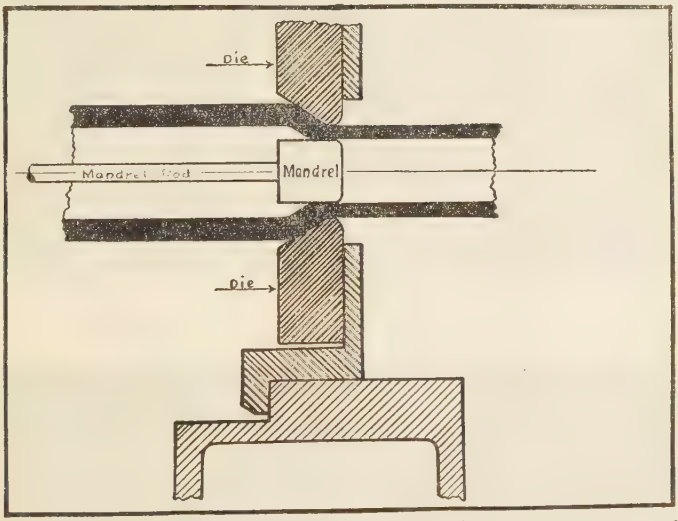


FIG. 328. Diagram showing relative position of die and mandrel in process of cold drawing of tubing.

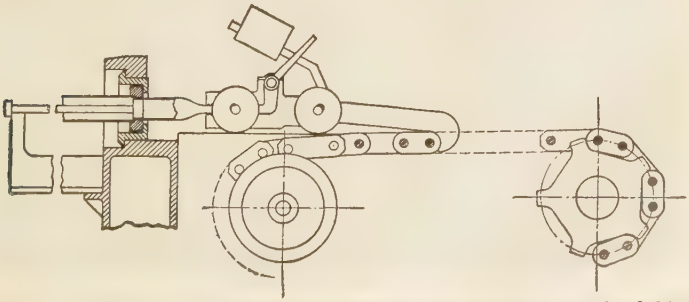


FIG. 329. Diagram of Draw-bench showing die and mandrel (on the left) with tongs and draw chain (on the right) with tube being drawn.

Preliminaries to Cold Drawing: In order to prepare the tubes, as received from the sizing rolls, for the drawing operation, they must be carefully inspected for surface defects, pointed, pickled, washed, dried and lubricated. In pointing a tube, a few inches of one end is heated to a moderate forging temperature and then swaged down between grooved dies in a small power hammer to a size somewhat smaller than the finished tube is to be, to form a bait that can easily be passed through the openings in the dies and be grasped by the drawing tongs of the draw bench. In swaging, care must be taken with the heating and hammering to see that the pointed end is concentric with the rest of the tube, as otherwise one important object of pointing, a uniform distribution of the drawing force, will not have been attained. Before the tubes can be drawn, they must be cleaned from scale, which, if allowed to remain, would score the dies and ruin the surface of the tube. After they have been pointed, therefore, the tubes are collected in bundles and lowered by crane into the pickling bath, a large wood-lined vat built in the floor of the shop and nearly filled with a two- or three-per cent. solution of sulphuric acid, which is heated and kept in constant agitation by jets of steam. After all the scale has been removed, a result that requires an immersion of from twenty to thirty minutes in the acid, the tubes are lifted out of the bath and immediately dipped several times in fresh water to wash off the acid. The tubes are then dried and lubricated with a mixture of tallow and flour. In general,

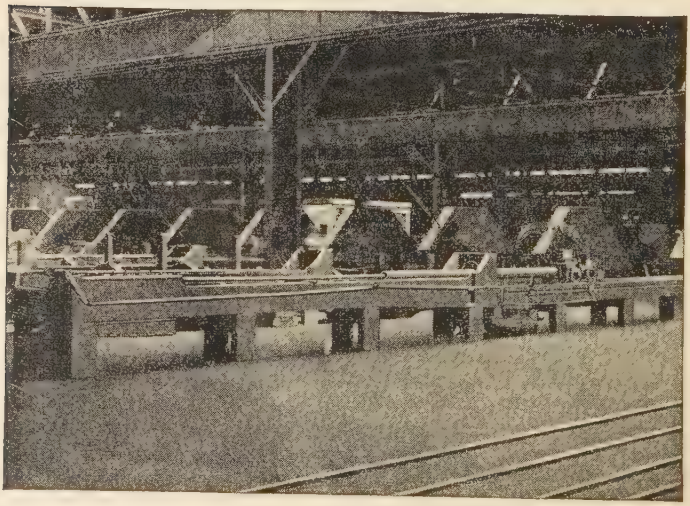


FIG. 330. General View of Draw-bench, showing tube being drawn through the die.

the tubes may be dried by allowing them to drain dry on an inclined surface, by blowing heated air over them, by laying them across a specially constructed hot pit, or by suspending them in racks over the annealing fur-

FIG. 331. Close-up View of Die for Cold Rolling Tubes, showing pointed end of tube projecting through die preparatory to attaching tongs.

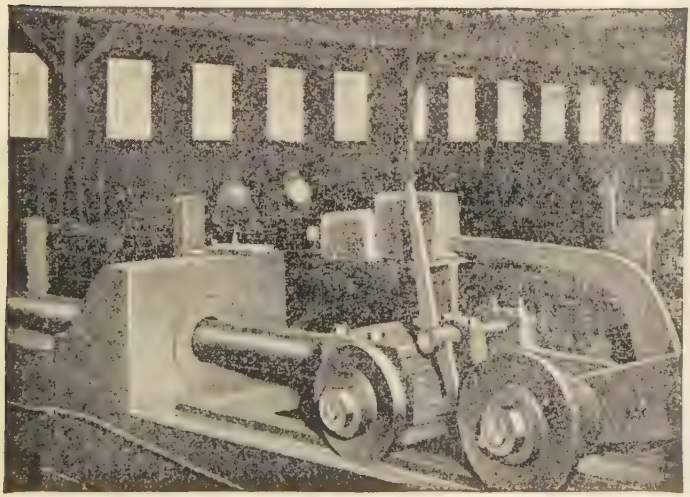


FIG. 332. Close-up View of Die and Tongs, showing tube being drawn through Die.

naces; and they may be lubricated either with the mixture mentioned above or with certain grades of oil by brushing or smearing the lubricant on or by dipping the tubes into it. The lubricant is more important with heavy than with light drafts. After being lubricated as required by the drawing to be done, the tubes are distributed to the draw benches for drawing.

The Cold Drawing Operations: Depending upon the inside diameter of the tubes to be drawn and their wall thicknesses, there are two methods of drawing, which might properly be called the drawing-over and the sinking method. In the first method, the tube as received from the pickling house is placed in front of the die on the draw bench, and its pointed end is inserted so as to project through the die. A workman then places a mandrel on the end of the mandrel bar and slides it into the tube from the opposite end, pushing it forward against the pointed end of the tube. The draw bench operator then attaches the drawing tongs to the pointed end projecting through the die and drops the hook at the other end of the tong truck, so that it engages a link of the draw chain. The tube and mandrel are drawn forward until the latter finds its position within the die, when, by a tremendous pulling force, the tube is drawn through the ring-like, or annular, space between the die and the mandrel. In this method, the thickness of the wall can be controlled to a certain extent as well as the diameter. If the wall of the tube is very heavy or if the inside diameter is one-half inch or less, the sinking method is used. In this method no mandrel is used inside the tube while drawing, and the reduction in the thickness of the wall cannot be controlled independently of the reduction in diameter.

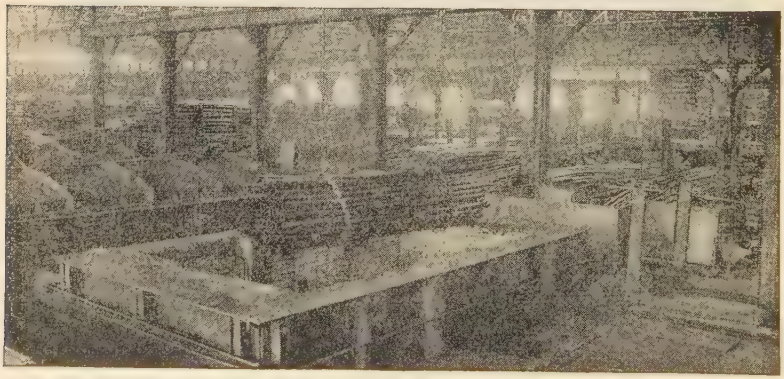


Fig. 333. Showing Charging of Furnace for Open Annealing.

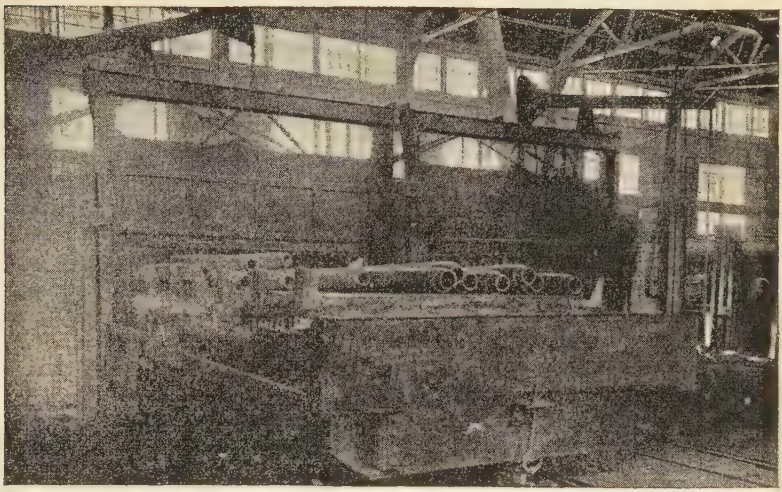


FIG. 334. Open Annealing Movable Bottom Furnace. Showing Tubes in place on bottom ready to be charged into furnace.

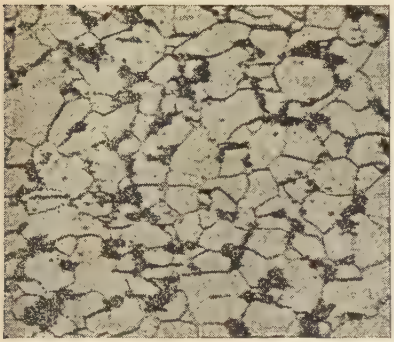
Annealing and Redrawing: One pass through a die is seldom sufficient to finish the tubes, and they must be redrawn, in some cases as often as twenty times, through dies of gradually decreasing diameters to obtain the dimensions desired. As cold drawing makes the tubes hard and brittle, it is necessary to anneal them after each pass in order to restore their ductility so that they may be drawn again. For this purpose, they are given a "light" anneal, that is, they are heated to a temperature not higher than 700° C. which, being just below the critical range, removes the drawing strains and prevents the formation of a heavy coat of scale. Following the annealing, the tubes must be pickled again to remove the thin film of black oxide formed in the furnace, when they are washed, dried, lubricated and redrawn as before, but through a smaller die.

Finish Annealing: After the final drawing operation, the tubes may be finish annealed at temperatures and by methods which vary according to the use for which they are intended, the type of steel, and the amount of reduction in cold drawing. Unless otherwise specified, low carbon plain steel tubes are given a light anneal, at a temperature but little above 500° C. This treatment leaves them with a dull but scale-free finish, relieves some of the drawing strains and stresses, restores much of their ductility, but generally does not efface all the effects of cold working, as may be observed from photomicrograph No. 3, page 1107. In general, the ductility increases with the annealing temperature, until at

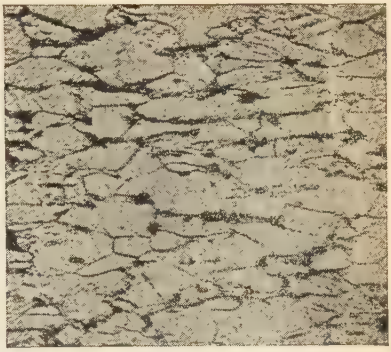
700° C. practically all the effects of the cold working are removed, as shown by photomicrograph No. 4. But between 600° C. and 800° C., the grain in moderately strained soft steels is liable to grow, in which case the tube loses strength without gaining much in ductility and is a more or less treacherous product. Consequently, whether so high an annealing temperature would be advisable in any specific case would depend upon the condition of strain and the type of steel, as well as the use to which the tube is to be applied. Only the ferrite is affected in this low temperature annealing. To bring about recrystallization of the pearlite and develop maximum softness in the tube, it must be given a full anneal, that is, be heated for a period of time just above its critical range. Three types of furnaces are employed for annealing at this plant, namely, the open fire furnace with fixed bottom and lifting doors in the ends, the removable bottom or car furnace, and the removable top furnace. The open fire and car furnaces may be used for light annealing small and large tubes, or full annealing large and heavy-walled tubing. The removable top, or pit, furnaces are used for annealing high carbon and alloy steels, which require particular heat treatment.

Finishing Cold Drawn Annealed Tubes: After the final anneal, the tubes must be straightened. This operation may be performed in three ways. The largest sizes are usually straightened on gag presses, medium sizes on roll straighteners, and small sizes on bending racks. With the roll machine the straightening of the tube is automatically performed by the machine itself, but in the other two methods the workman's eye and judgment must be depended upon to secure the desired result. The straightened tubes are now sent to cutting-off machines, where they are cut to lengths specified or to best advantage in random lengths, when they are inspected and tested in accordance with the specifications.

Mechanical Tubing: At the Ellwood Works tubing for mechanical purposes is made in a wide range of sizes and thicknesses, and in many different shapes. Some of these shapes are oval, square, octagon, hexagon, flat or rectangular, etc. To produce these different shapes, tubing of the proper size is passed through rolls or drawn through a machine similar to the draw-bench, but instead of a die, a set of small rolls, held in position by a frame in the proper relation to each other, is provided.

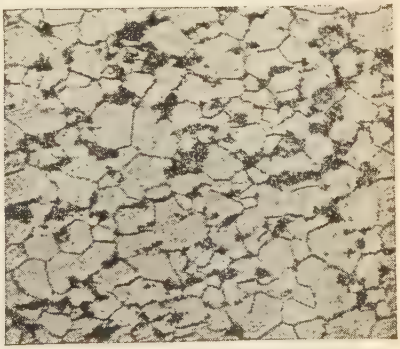


1. Hot Finished Tube. x200. As Rolled



2. "Green" Tube. x200. After Cold Drawing

3. "Finish" Annealed Tube. x200. Annealing Temperature 500°C.



4. "Medium" Annealed Tube. x200. Annealing Temperature 700°C.

5. "Soft" Annealed Tube. x200. Annealing Temperature 900°C.

FIG. 335. Photomicrographs Showing Average Structures of Seamless Steel Tubes of .10- to .20-per cent. Carbon Grade, after Treating as Indicated. The black areas are pearlite. The light ones, ferrite.

The Cupping Process: The cupping process is employed by the National Tube Company at their Christy Park Plant. Although, when first patented in 1851 by Remond, in England, it was intended for making all sizes of tubes, it is now used only in the manufacture of the larger sizes. It is practicable now for all sizes larger than five inches, but since tubes up to nine and a half inches can be made so readily by the piercing processes already described, it is seldom employed for any sizes smaller than nine inches, except for the manufacture of cylinders or couplings. The greatest drawback to the method, when applied to the small sizes, is the difficulty of making the tubing in long pieces; but as large seamless tube is seldom required in lengths of more than ten or twelve feet, it is the most economical and advantageous method to employ on these large sizes. The maximum lengths it is possible to make vary from ten to twenty feet, according to the size of the tube and other conditions.

Chief Details of the Cupping Process: Although the operation of the cupping process requires considerable skill and experience, the principles of the process are simple and easily understood, hence it may be only

FIG. 336. View of Press Punching Disc from Square Plate Preparatory to first Cupping Operation.

briefly described here. The steel is delivered to the tube works in the form of square plates the sizes of which are calculated to contain the necessary volume of metal for the finished tube, plus a sufficient amount to compensate for normal losses in manufacture. These sizes may vary from two to seven feet square, and from ⅜ inch to 4 inches in thickness. The smaller sizes of these plates are heated to a forging temperature in a suitable furnace, and placed in a press provided with circular dies, where a circular plate, or disc, is punched out of each plate. Since this operation does not cool the plates to a great extent, they are immediately passed to a second press, where they are placed in a position concentric with a circular opening in a bottom die, and then pushed through it with a round nosed plunger from above. The hollow cup thus formed is then recharged into a heating furnace to restore the forging temperature. When the temperature has been restored, the cups are pushed through a smaller die provided with a special opening to fit the bottom of the first cup. This second operation deepens the cup, and, at the same time, reduces its diameter and leaves it practically cylindrical.

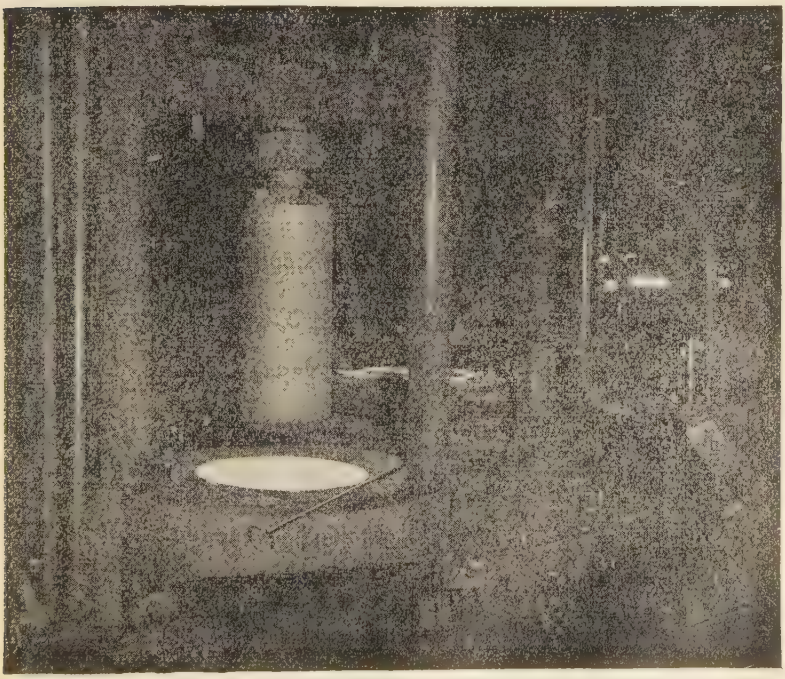


FIG. 337. View of Press Starting First Cupping Operation.

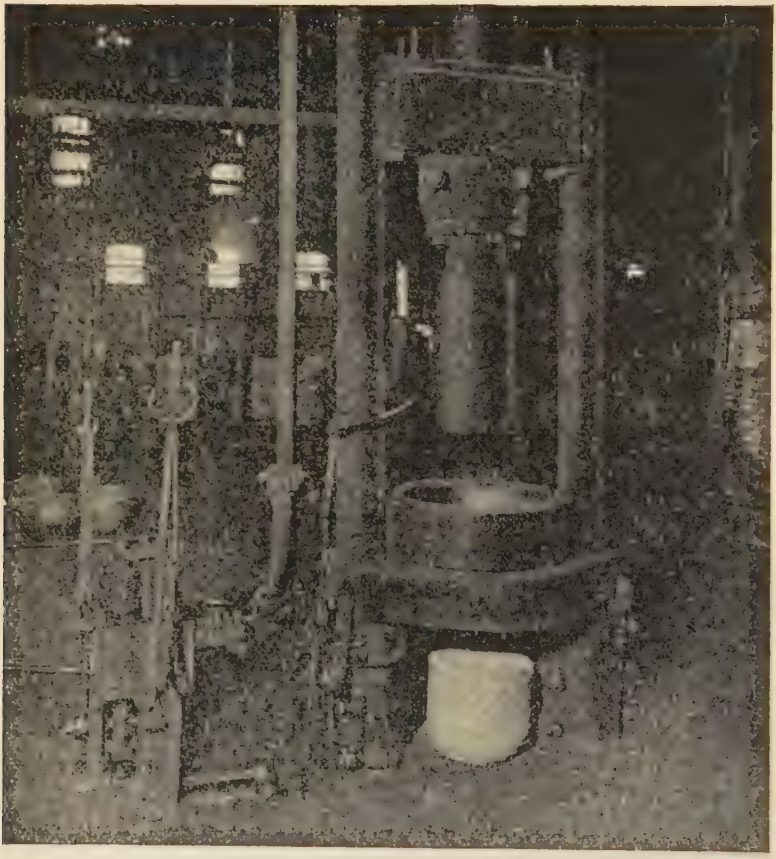


FIG. 338. View of Press Completing the Second of the Two Cupping Operations.

Plates for the largest sizes are cut into the disc form before heating, usually on a boring machine, though the oxyacetylene torch has also been used for this purpose. These discs are then heated and cupped in much the same process used for the smaller sizes.

Hot Drawing the Cupped Piece: After the final cupping process, the cup is again reheated preparatory to hot drawing on the horizontal bench. This apparatus consists of a heavy, cast steel, trough-like frame, provided in each side with suitable recesses for the insertion of dies and

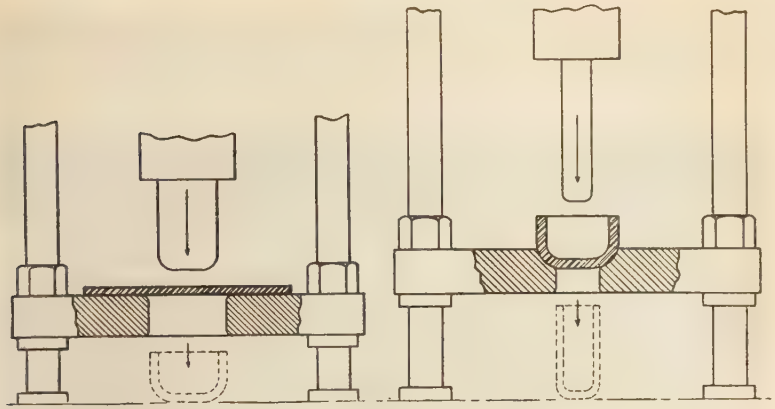


Fig. 339. Diagrams of First (left) and Second (right) Cupping Operations.

Fig. 340. Boring Mill Cutting Discs from Heavy Plates.

at one end with a powerful hydraulic plunger long enough to operate through the full length of the bench. A punch of a size corresponding to the inside diameter of the tube desired is placed on the end of the plunger, and a series of from 3 to 12 dies of successively decreasing diameters are dropped into the recesses of the bench-frame, which supports them all in a

bar. The reheated cup is now dropped into the bench trough, between the dies and the plunger, so that its closed end points into the first and largest of the dies. The plunger now advances, enters the cup, and pushes

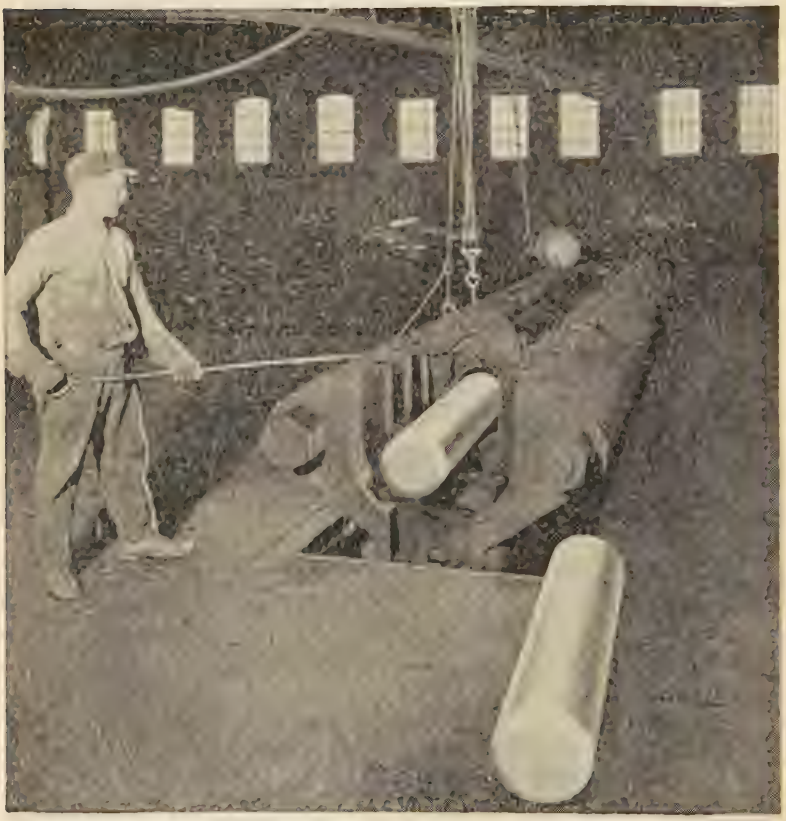


Fig. 341. Hot Draw Bench in Operation.

it slowly through the whole series of dies, elongating it and reducing its wall thickness and diameter at the same time. As the drawing pressure is limited to a force less than that required to punch through the closed end of the cup, the operations of heating and drawing may have to be repeated several times, in some cases as often as nine times, to draw the tube down to the dimensions required. At the end of the last operation, the plate has taken on the form of a tube with one end closed, which

may be cut off to form a true tube, or allowed to remain to form the bottom of a cylinder, depending on the size and use to which the tube is to be put. All tubes that may require it, are straightened in a gag press specially designed for the purpose. After the usual inspection and testing, the process, so far as the tube making is concerned, has been completed. When necessary, the hot drawn tubes, from 6 to 9 inches in size, may be cold drawn, or cold drawn and annealed, when these operations are carried out as already described under the finishing of tubes made by the piercing processes.

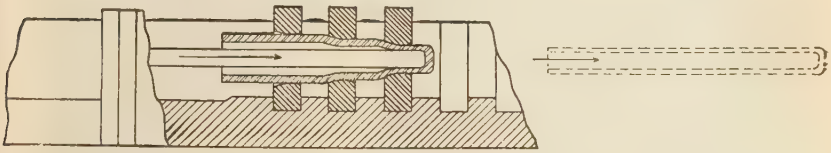


FIG. 342. Diagram illustrating Principle of Hot Draw Bench.

FIG. 343. View of Hot Draw Bench. Showing how the bottom of a cylinder may be formed at the end of the hot drawing operation.

Forming Cylinders: To form the necks of large cylinders (over 6″ in diameter), the open end of the tube, after careful inspection, is trimmed evenly, heated to a forging temperature, and swaged under a hammer as shown in the cuts below.

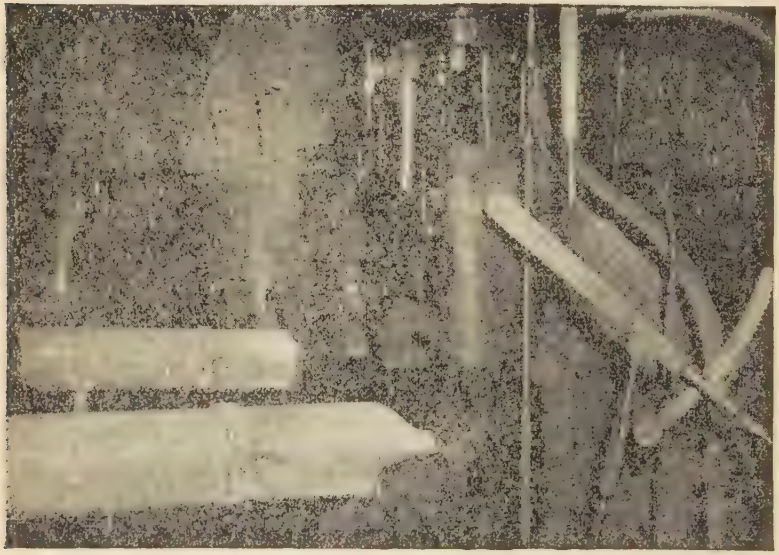


Fig. 344. Furnace and Hammer Swaging one End of a Tube to Form the Open End of a Cylinder.

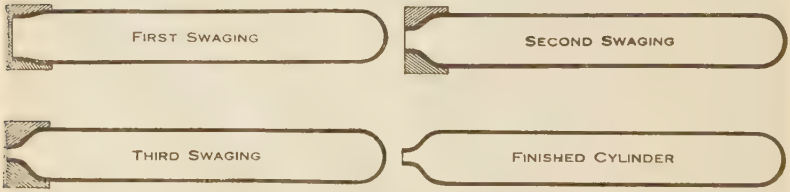


Fig. 345. Diagram of the Swaging Operations.

Spinning: Another method for contracting or closing the ends of seamless tubes is known as spinning. This method is generally applied in the manufacture of small cylinders (6 inches and under), for with it the end of a tube may be closed and perfectly welded in the same operation. This interesting process is very simple both in principle and operation. It is accomplished by means of a spinning machine, which is nothing more

than a type of lathe with a hollow spindle provided with a clutch for holding the tubes in correct position for spinning. In carrying out the process, the end of the tube to be spun is heated to a dull red color, the tube is placed in the lathe, the spindle is rotated at a high speed (1200 to 1400 r. p. m.), and a blunt tool of high speed steel is brought to bear against the heated part of the tube and slowly swung around the end of it. The friction of this tool against the tube generates heat at a high rate, and by repeatedly manipulating the tool the temperature may be raised to the point of incipient fusion for the steel of the tube. The accompanying cut shows the different steps in the operations of closing the end of a tube. This cut shows that, with each sweep of the tool around the end of the tube, the metal is gathered closer and closer towards the center, until, at the sixth sweep, the heat at the center has become so intense as to melt the metal, thus closing the opening with a perfect weld.

FIG. 346. Ends of a Tube at Different Stages of the Spinning Process, Showing the progress of the operation from the tube on the left to the closed cylinder on the right.

Advantages and Uses of Seamless Tube: From these descriptions of the processes of manufacture, the reader will perceive that hot finished seamless steel tube can now be made by the piercing process, at least, with almost as much ease and rapidity as lap-welded tube and pipe. In spite of this fact, however, there are many reasons why seamless tubing should be, and continue to be, somewhat more costly than welded material. A portion of this difference in cost is due to the extra fine quality of steel required to make the seamless product, to produce which only the open hearth or the electric process can be used, a generous discard from the ingot must be made, and all surface defects must be eliminated by the tedious processes of chipping and grinding. Any further difference in cost is evident from the additional operations necessary to produce the seamless products and the complicated nature of the machinery used as compared with that to produce the welded products. In regard to the cold finished tubing, it requires no more than the description just given to show that the annealing and drawing operations are costly ones. Seamless steel tubing, however, has many advantages that justify its use by manufacturers and overbalance the extra cost to the consumer, and that makes it, besides, indispensible in the manufacture of many things. The number of cases that might be cited to illustrate and demonstrate this statement are almost innumerable, but a few lines of manufactured articles may be mentioned as examples, such as marine and locomotive boilers; automobiles, especially as rear axle housings and parts of the engine and steering apparatus; agricultural implements; airplanes and airships; bicycles

and motor cycles; dental and surgical instruments; mandrels for making rubber goods; household articles, such as vacuum sweepers, sewing machines, ammonia-cooled refrigerators and cream separators; telescopes and other scientific instruments; toys, such as tricycles and pistols; torpedoes; tools of various kinds; musical instruments; and so on. Hot drawn tubing is extensively used in place of castings and forgings for columns and for pistons of hydraulic and other apparatus. Another important use of the hot drawn tubing is in the manufacture of cylinders, or containers, for liquids and gases under high pressure, such as carbonic acid gas, oxygen, ammonia gas, acetylene, etc.

Steel for Seamless Products: The advantages which make seamless tubing so adaptable, are the facts that it can be made of almost any class of steel chemically, whether of the plain carbon or of the alloy class, and that the steel, of whatever class, must be free from all those mechanical, or physical defects, and many of the chemical defects, that occur in ordinary steel and render it unfit to withstand severe forging, pressing, and quenching operations. For 1925-26, the National Tube Company have adopted four different grades of carbon steel as standards for use in the manufacture of seamless tube. These are shown in the accompanying table.

Table 104. Showing Standard Carbon Steels for the Manufacture of Seamless Tubes and Tubing.

GRADES OF STEEL	ANALYSIS			
	Carbon %	Manganese %	Phosphorus Maximum %	Sulphur Maximum %
Boiler Tube	.08—.18	.30—.60	.040	.045
.10—.20 Carbon	.10—.20	.30—.60	.040	.050
.20—.30 Carbon	.20—.30	.40—.65	.040	.050
.30—.40 Carbon	.30—.40	.40—.65	.040	.050

In addition to these standard steels, tubes for special purposes are made from special steels, such as higher carbon steel, chrome-vanadium steels, high-carbon high-chrome steels, nickel steels, etc. The physical qualities of all these steels vary with their heat treatment, especially after hot rolled tubes undergo the cold drawing operation, which hardens the steel. The boiler tube grade of steel is especially suitable for boiler tubes and for any other tube purposes requiring great ductility. The higher carbon grades of steel tubes are suitable for purposes in which higher yield point and tensile strength are required. Nickel steel tubes and other alloy grades are suitable for materials requiring great ductility combined with high elastic limits and ultimate strengths.

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